ZP501

Independent analysis and reporting of ZX Lidars performance verification executed by ZX Lidars at the UK Remote Sensing Test Site

ZX Lidars

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Table of contents

1 INTRODUCTION 3

2 DESCRIPTION OF THE TEST SITE 4
2.1 The UK Remote Sensing Test Site 4
2.2 Measuring equipment 5
2.2.1 Meteorological mast: layout, sensors distribution and data acquisition 5
2.2.2 The ZP300 Lidar 8

3 LIDAR PERFORMANCE VERIFICATION APPROACH 9
3.1 Common test conditions and data filtering 9
3.2 Sector filtering 9
3.3 Data coverage requirements for accuracy assessment 10
3.4 LPV evaluation 10

4 RESULTS 11
4.1 System availability 11
4.2 Data availability 12
4.3 Data filtering 13
4.4 Wind speed comparison 13
4.5 Wind direction comparison 17
4.6 Performance verification according to revised IEC standard, Annex L 18
4.6.1 Performance verification uncertainty 20

5 IMPORTANT REMARKS AND LIMITATIONS 28

6 CONCLUSION 29

7 REFERENCES 31

8 GLOSSARY 32

Appendices

APPENDIX A KEY PERFORMANCE INDICATORS AND ACCEPTANCE CRITERIA [2] 33

APPENDIX B UK REMOTE SENSING TEST SITE NEAR PERSHORE/THROCKMORTON MET MAST DETAILS 36

APPENDIX C TIME SERIES OF WIND SPEED 39

APPENDIX D WIND DIRECTION 40

APPENDIX E CUP CALIBRATION CERTIFICATES 42

APPENDIX F IEC ANNEX L UNCERTAINTY ANALYSES 74

APPENDIX G ENVIRONMENTAL CONDITION DURING THE VERIFICATION CAMPAIGN 75

List of Tables

Table 1: List of meteorological sensors and individual anemometers installed at the mast during verification campaign, as of Appendix B. 7
Table 2: List of calibration factors for cup anemometers. The valid calibration certificates are attached to this report in Appendix E. 7
Table 3: Height settings of ZP300 Lidar and reference mast. Levels for wind speed and wind direction comparisons are highlighted in bold letters. 8
Table 4: Number of 10-minute data points after filtering used for WS comparison at each of the four (4) levels. 11
Table 5: Summary of system and data availabilities. 11
Table 6: Regression results for comparison; acceptance relevant results are colour shaded. 15
Table 7: Summary of absolute wind speed differences between cups and Lidar. 15
Table 8: Summary of WD comparison results for both comparison levels 17
Table 9: Statistical parameters of wind speed deviation 20
Table 10: Uncertainty calculation for 21 m level. 24
Table 11: Uncertainty calculation for 46 m level. 25
Table 12: Uncertainty calculation for 71 m level. 26
Table 13: Uncertainty calculation for 92 m level. 27
Table 14: List of KPIs and ACs relevant for System and Data Availability assessment 33
Table 15: List of KPIs and ACs relevant for Wind Data Accuracy assessment 34

List of Figures

Figure 1: Map of the UK Remote Sensing Test Site near Pershore/Throckmorton, in UK. The position of the reference mast is marked by a red dot. 4
Figure 2: Schematic of the sensor level and boom distribution at the 90.5 m mast, as taken from [1]. 6
Figure 3: Typical setup of ZX Lidars next to the reference mast at the UK Remote Sensing Test Site. 8
Figure 4: Wind direction sectors used to select undisturbed wind speed data from oppositely arranged cup carrying booms for comparison. 10
Figure 5: Lidar system and data availabilities for all measurement levels. 12
Figure 6: Plots of linear wind speed regression results for 21, 46, 71 and 92 m 16
Figure 7: Regression plot of wind direction comparisons at 88 m (left) and 43.5 m (right) 17
Figure 8: Comparison of the horizontal wind speed component at 21 m 18
Figure 9: Comparison of the horizontal wind speed component at 46 m 19
Figure 10: Comparison of the horizontal wind speed component at 71 m 19
Figure 11: Comparison of the horizontal wind speed component at 92 m 20
Figure 12: Bin-wise comparison of the horizontal wind speed component at 21 m 21
Figure 13: Bin-wise comparison of the horizontal wind speed component at 46 m 21
Figure 14: Bin-wise comparison of the horizontal wind speed component at 71 m 22
Figure 15: Bin-wise comparison of the horizontal wind speed component at 92 m 22

1 INTRODUCTION

GL Garrad Hassan Deutschland GmbH ("GH-D"), a member of the DNV GL Group ("DNV GL"), has been assigned on 2019-09-05 by ZX Lidars to prepare an independent analysis and report of a Remote Sensing Device (RSD) performance verification conducted by ZX Lidars. In this analysis and report the ZX Lidar with the serial number ZP501 will be discussed. The verification measurements for this device were performed by ZX Lidars at their UK Remote Sensing Test Site near Pershore/Throckmorton, in UK between 2019-08-09 and 2019-09-02.

The meterological reference mast (met mast) was equipped with classical anemometry components (cup anemometers, wind vanes etc.) serving as the verification reference for the Lidar wind speed and wind direction comparisons. Those comparisons were performed in line with a Remote Sensing (RS) best practice verification approach as developed within the EU-FP7-Projekt NORSEWInD [1] against corresponding Key Performance Indicators (KPIs) and Acceptance Criteria (ACs; compare APPENDIX A).

In addition, a performance verification and uncertainty calculation is carried out in accordance with the current edition of the reviewed IEC 61400-12-1 standard, Annex L [3].

DNV GL is accredited according to ISO 17025 for measurements on wind turbines and for wind resource measurements,energy assessments and Lidar verifications. DNV GL is also a full member of the network of measurement institutes in Europe 'MEASNET' and in the FGW (Fördergesellschaft Windenergie und anderer Erneuerbaren Energien).

The work has been conducted in compliance with all relevant health and safety legislation. GL Garrad Hassan Deutschland GmbH operates an Occupational Health and Safety Management System certified according to the OHSAS 18001:2007.

2 DESCRIPTION OF THE TEST SITE

2.1 The UK Remote Sensing Test Site

The following description and figures of the UK Remote Sensing Test Site, which is a disused air field, are taken from a technical report by ZX Lidars. [1]:

The terrain in the vicinity of the mast is flat and covered with sparse low growing vegetation. A freestanding lattice tower of approximately 40 m in height exists on a bearing of 270° at 230 m from the mast. A number of hangars and outbuildings exist in sectors between 260° and 317° at distances between 300 m and 700 m from the mast. These buildings are estimated not to exceed 14 m in height. Approximately 500 m to the North-East lies the small village of Throckmorton which consists of a few scattered farms and houses. 700 m to the South-West of the mast between 190° and 240° lies an area of spoil heaps and filtration pools associated with a mining operation. On a wider scale the site is surrounded by flat arable land that is devoid of any dense closed canopy forest. The larger conurbations of Pershore and Evesham lie at distances of 5 km and 9 km to the South West and South East respectively.

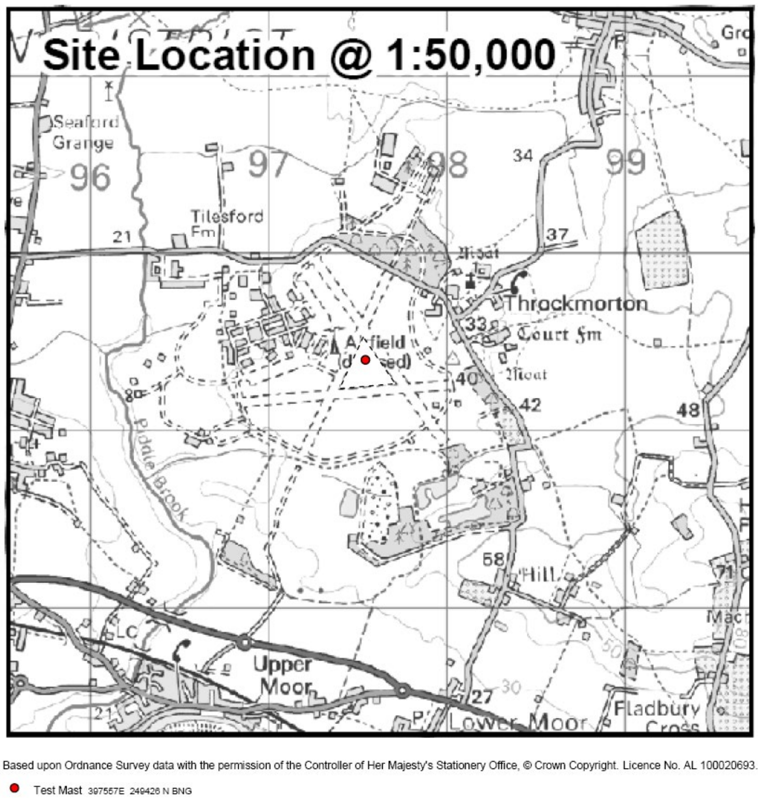


Figure 1: Map of the UK Remote Sensing Test Site near Pershore/Throckmorton, in UK. The position of the reference mast is marked by a red dot.

The site specifications given in the above description have been verified during a site visit by a DNV GL expert on 2018-04-18, see [6]. Further details on the site are given in [1], a 360° photo round is shown in Appendix B.

2.2 Measuring equipment

In the following sections technical details and specifications of the measuring equipment are described. This description covers the met mast including its sensors and data acquisition system as well as the tested Lidar.

The following items regarding the meteorological measurement systems have been verified during the above mentioned site visit:

- Site suitability and exact positions of mast and Lidar test stand
- Mast height, measurement levels and boom orientations
- Distribution and mounting of sensors at the mast
- Validity of MEASNET [5] calibrations of cups and correct application of calibration factors and offsets
- Wind vane offset
- Data acquisition components, logger configuration
- Data storage and data provision

2.2.1 Meteorological mast: layout, sensors distribution and data acquisition

The following description is taken from [1]:

The met mast has been constructed to be fully compliant with the edition of IEC 61400-12-1 [3] and the terrain of the test site falls within requirements for testing without a site calibration. All cup anemometers installed on the reference mast are class 1A instruments as defined by [3] and have undergone individual rotor specific MEASNET [5] calibration at a MEASNET certified wind tunnel.

All boom and upright dimensions have been determined using the lattice porosity and mast dimensions provided by the manufacturer and in compliance with [3] to operate within a maximum flow distortion of 0.5% at the wind measurement locations. The directional vane is installed with their North marking aligned along the booms towards the mast. The boom orientation is compensated for in the data logger.

The main mast installation documents (as presented in [1]) are included for reference in Appendix B and the instrument calibration certificates are included in Appendix E. Those calibrations belong to the most recently changed anemometers, hence being valid for the wind speed sensors of the met tower during this verification campaign.

The met mast is a guyed 90.5 m triangular lattice tower with a face width of 0.7 m. The MEASNET calibrated [5] cup anemometers (cups) of type Thies Frist Class Advanced (TFCA) are mounted on booms aside the mast at heights of 20.5 m, 45.5 m and 70.5 m and in a top mounting position at 91.5 m A.G.L., see Figure 2. Those mounting arrangements are consistent with the IEC [3] and IEA [4] recommendations for the use of cup anemometry at masts.

The mounting of two anemometers (Thies First Class) in a 'goal-post' configuration is considered acceptable. The horizontal distance between the two poles is 2.0 m, compare Appendix E. Hence DNV GL considers the goal-post mounting of top instruments to be broadly in line with the applicable updated IEC standards [3]. The distance of 2.0 m between the two poles is slightly under the IEC recommendation of > 2.5 m. The met mast influence on the cup anemometers has been understood very well and DNV GL states that the separation distance of the two top sensors in a 'goal-post' configuration has no negative impact in this setup. It should be noted that the met mast is fully compliant with the edition 1 of IEC 61400-12-1.

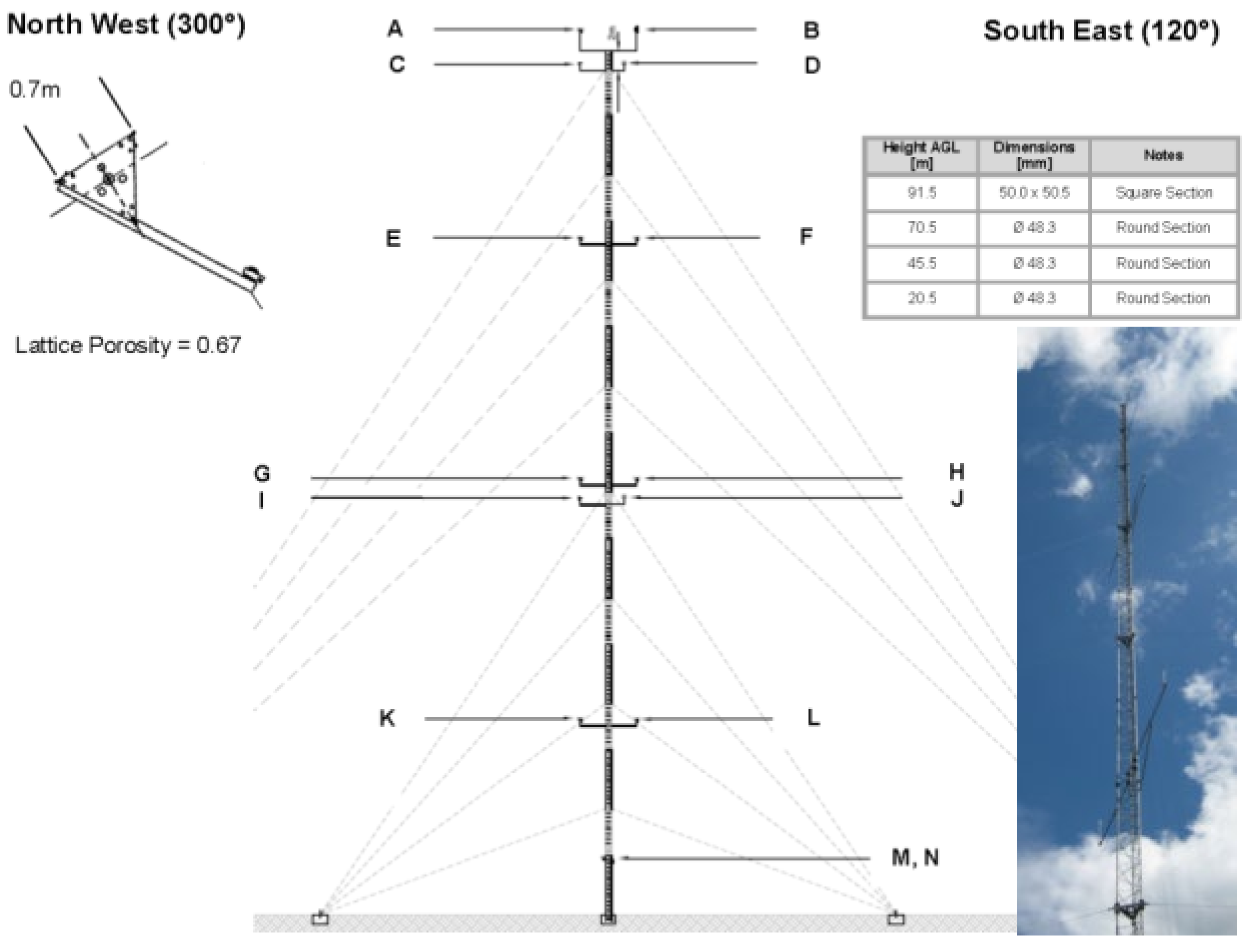


Figure 2: Schematic of the sensor level and boom distribution at the 90.5 m mast, as taken from [1].

Table 1 shows the technical specifications of the mast. Table 2 lists the different sensors and serial numbers. Respective calibration certificates for each sensor are given in Appendix E. The photo in the right box of Figure 2 shows mast anemometry levels between 20.5 and 91.5 m AGL.

The position of the test stand (Lidar / met mast) in terms of the WGS84 standard is:

- **Lat** N 52° 08' 35"
- **Lon** W 02° 02' 14"

Label	Height [m]	Orientation - Mast to Instrument [°]	Instrument Type	Instrument Model	Cup to Boom Centre Height [mm]	Instrument to Mast Centre Length [mm]
A	91.5	300	Cup Anemometer	Thies First Class Advanced	1520	1025
B	91.5	120	Cup Anemometer	Thies First Class Advanced	1500	1025
C	88	300	3D Sonic Anemometer	Thies Clima 3D Sonic Anemometer	920	3700
D	88	120	Temperature/Humidity	Campbell Scientific CS215	-	-
E	70.5	300	Cup Anemometer	Thies First Class Advanced	960	3700
F	70.5	120	Cup Anemometer	Thies First Class Advanced	915	3700
G	45.5	300	Cup Anemometer	Thies First Class Advanced	955	3700
H	45.5	120	Cup Anemometer	Thies First Class Advanced	1160	3700
I	43.5	300	Direction Vane	Vector W200P	920	3700
J	43.5	120	Temperature/Humidity	Campbell Scientific CS215	-	-
K	20.5	300	Cup Anemometer	Thies First Class Advanced	960	3700
L	20.5	120	Cup Anemometer	Thies First Class Advanced	930	3700
M	-	-	Pressure	Campbell Scientific CS100	-	-
N	-	-	Data Logger	Campbell Scientific CR 1000	-	-

Table 1: List of meteorological sensors and individual anemometers installed at the mast during verification campaign, as of Appendix B.

Label		A	B	E	F	G	H	K	L
Channel		WS_2R	WS_1M	WS_4R	WS_3V	WS_6R	WS_5V	WS_8R	WS_7V
Model		Thies First Class Advanced	Thies First Class Advanced	Thies First Class Advanced	Thies First Class Advanced	Thies First Class Advanced	Thies First Class Advanced	Thies First Class Advanced	Thies First Class Advanced
S/N		11183812	10164580	11183813	7162397	7162398	11183815	11183814	7162399
Height [m]		91.5	91.5	70.5	70.5	45.5	45.5	20.5	20.5
Orientation - Mast to Instruments [°]		300	120	300	120	300	120	300	120
DWG	Calibration date	20-11-18	22-11-16	20-11-18	10-10-17	10-10-17	20-11-18	20-11-18	10-10-17
	Slope	0.04602	0.04589	0.04606	0.04612	0.04609	0.04594	0.04602	0.04609
	Offset	0.2282	0.2519	0.2256	0.2278	0.2392	0.2362	0.2233	0.2273
Applied		0.04602	0.04589	0.04606	0.04612	0.04609	0.04594	0.04602	0.04609
		0.2282	0.2519	0.2256	0.2278	0.2392	0.2362	0.2233	0.2273

Table 2: List of calibration factors for cup anemometers. The valid calibration certificates are attached to this report in Appendix E.

2.2.2 The ZP300 Lidar

The Lidar under test is a ZX Lidar of type ZP300 slimline Doppler Wind Lidar, employing a CW laser (continuous wave laser) that has specifically been designed to measure wind speeds at heights in the boundary layer of the atmosphere. The serial number of this individual device is ZP501. During the measurement campaign the Lidar system was configured to record wind speed measurements at 11 different levels between 21 and 201 m. The actual Lidar measurement heights can be seen at Table 3. The four heights at 21, 46, 71 and 92 m were used for the comparison to the cup/mast reference measurements.

Figure 3 shows an array of ZX Lidars under test being typically located to the East of the base of the met mast, and Table 3 lists wind speed and wind direction measurement and comparison levels as given and selected for the performance verification.

Figure 3: Typical setup of ZX Lidars next to the reference mast at the UK Remote Sensing Test Site.

	Height Settings (relative to ground level)										
Device	**Measurement Levels [m]**										
ZP300	**21.0**	39.0	**46.0**	**71.0**	**92.0**	106.0	121.0	141.0	161.0	181.0	201.0
Mast/WS-Cup	**20.5**		**45.5**	**70.5**	**91.5**						
Mast/WD-Vane/3D Sonic			**43.5**		**88.0**						

Table 3: Height settings of ZP300 Lidar and reference mast. Levels for wind speed and wind direction comparisons are highlighted in bold letters.

3 LIDAR PERFORMANCE VERIFICATION APPROACH

3.1 Common test conditions and data filtering

In the process of the Lidar Performance Verification (LPV) trial the following test conditions and filters are applied

- All comparisons are based on 10-minute average wind values returned from wind vanes/3D Ultrasonic anemometer and MEASNET calibrated cup anemometers installed on the reference mast (primary reference) and concurrent wind direction and wind speed data from the Lidar under test.
- All other reported data (particularly wind speed) within undisturbed free-stream wind direction sector relative to the reference mast as well to the Lidar are used in the comparison analysis.
- For the validation of Lidar wind speeds against the mast the wind speeds from TFCA cup anemometers at 20.5 m, 45.5 m, 70.5 m and 91.5 m are used. The Lidar data are selected according to the sector screening of the cup data prior to comparison, see following section.
- No Lidar specific quality filters are applied to the measured Lidar data prior to the analysis conducted.
- All data collected during periods of possible icing at cup anemometers, i.e. with temperatures below 0.2 °C near mast top height are excluded.

3.2 Sector filtering

The orientation of cup carrying booms at the mast is to the North West at one side and to the South East on the other side. Hence, wind speed data need to be screened at wind directions between 85° and 155° for cups on the Northwest side of the mast and between 265° and 335° for cups on the Southeast side of the mast. This sector screening of 70° per boom directions accounts for downwind mast wake effects on the boom mounted instruments, see sector sketch in Figure 4.

If cup data from both boom directions is available (i.e. for wind directions out of the remaining two sectors), the wind speed average of the two oppositely mounted instruments is used as reference for the comparison with the Lidar wind speeds. In this case data are further screened for the wind speed difference between both cups to exceed 0.3 m/s. Within the two disturbance sectors wind speed data from a single cup, i.e. from the one mounted on the upwind directed boom is considered valid, only.

Cup data at the 91.5 m and 70.5 m levels are screened against wind direction data from ultrasonic anemometer at 88.0 m. Instruments at 45.5 m and 20.5 m are screened against wind direction data from a vane at 43.5 m.

For the validation of ZX Lidar wind speeds against the mast, only wind speeds from the cup anemometers are used as reference.

No Lidar specific filters were applied to the measured Lidar data prior to the analysis conducted.

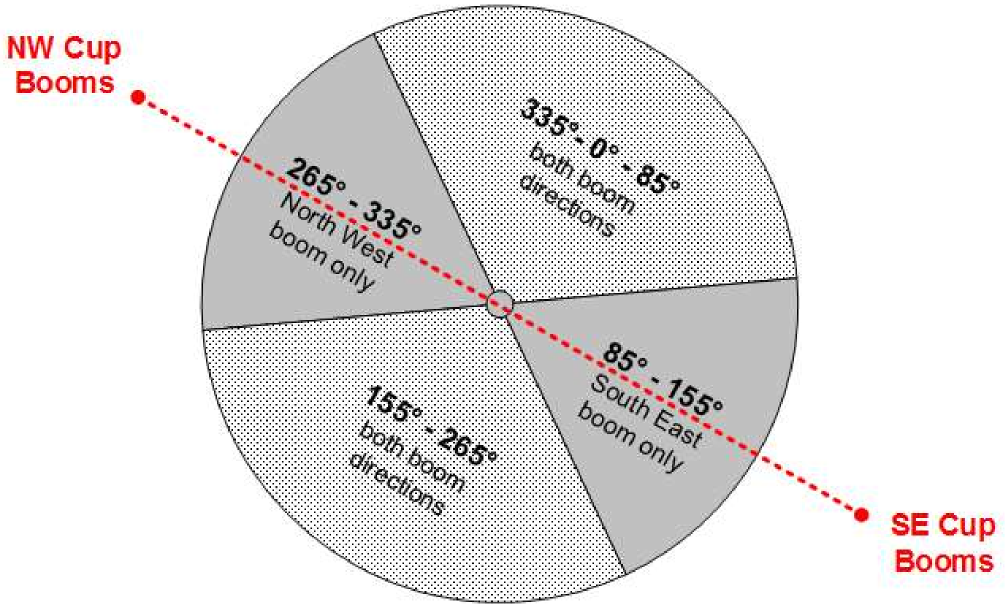


Figure 4: Wind direction sectors used to select undisturbed wind speed data from oppositely arranged cup carrying booms for comparison.

3.3 Data coverage requirements for accuracy assessment

The following data coverage definitions are prescribed for the LPV:

- The overall minimum number of 10-minute data points after filtering (according to sections 3.1 and 3.2) for the WS ranges [all > 3 m/s] and [4 to 16 m/s] should not be lower than 600.
- At least 200 10-minute data points should to be in the WS range between 4 and 8 m/s and 200 data points between 8 and 12 m/s.

Those data coverage requirements are regarded as achievable for a typical test period of 4 weeks.

3.4 LPV evaluation

The performance of the Lidar under test is evaluated for its system and data availability as well as for its wind data accuracy, based on a number of Key Performance Indicators (KPI) and according Acceptance Criteria (AC).

The evaluation approach in terms of the applicable KPIs and according ACs is outlined in Appendix A, where KPIs and ACs for system and data availability are listed in Table 14 those for wind data quality in Table 15.

The performance assessment of the given KPIs and respective Acceptance Criteria regarding Availability and Accuracy is executed at each reference level present, in this case at each of the four (4) met tower's 1st Class reference anemometry levels which are 20.5 m, 45.5 m, 70.5 m and 91.5 m a.g.l.

4 RESULTS

For the treated LPV campaign data were provided for the period 2019-08-09 until 2019-09-02. So the campaign was completed after 24 days. The verification trial covered wind speed ranges of 3.0 to 20.2 m/s at the upper mast level (91.5 m) and 3.0 to 16.2 m/s at the lower mast level (20.5 m). The data coverage per wind speed range, as defined in section 3.3, can be seen in Table 4.

	# of Data points			
WS-range	**92**	**71**	**46**	**21**
All >= 3 m/s	3084	3035	2937	2655
4 - 8 m/s	1574	1714	1766	1677
8 - 12 m/s	1087	901	675	410
4 - 16 m/s	2858	2784	2635	2242

Table 4: Number of 10-minute data points after filtering used for WS comparison at each of the four (4) levels.

The completeness requirements as of section 3.3 are fulfilled for all WS ranges.

4.1 System availability

The system availability as applied to the Lidar device is defined by a percentage of the maximum possible number of ten-minute periods within campaign duration of 24 days, which represents 3456 concurrent data points. As 3456 Lidar ten-minute data entries were present (regardless of the data validity), the Lidar device achieved a system availability of 100 % see Table 5.

	LiDAR Availability Assessment			
Height / m	**92**	**71**	**46**	**21**
Max. # of 10-min points in period	3456	3456	3456	3456
After accounting power outages	3456	3456	3456	3456
Data present	3456	3456	3456	3456
System availability (**KPI SA_{CA}**)	100.0%	100.0%	100.0%	100.0%
Total # of 10-minute valid data	3404	3410	3419	3436
Data availability (**KPI DA_{CA}**)	98.5%	98.7%	98.9%	99.4%
# after external filtering	3084	3035	2937	2655
Data availability for comparison	89.2%	87.8%	85.0%	76.8%

Table 5: Summary of system and data availabilities.

✓ The Acceptance Criterion for System Availability (**KPI** SA_{CA}) to be ≥95 % is successfully met at all heights.

4.2 Data availability

Table 5 summarizes the period of overlap between met-mast and Lidar system during the measurement campaign with the system availability of 100% as stated in the previous section. It shows a data availability for the treated comparison measurement levels between 21 and 92 m A.G.L. – regardless of the relevance for wind data comparisons – between 98.5 % and 99.4 % relative to the net campaign maximum possible number of ten-minute periods.

- ✓ The Acceptance Criterion for Data Availability (**KPI** DA_{CA}) to be ≥90 % is successfully met for all measurement levels.

Data for individual heights were treated as available when they show a numeric value in contrast to a value being flagged as NaN (not a number). The difference in number of available data between the rows "system" and "data availability" Table 5 reflect the reduction of valid data according to internal system filtering.

This can be seen in Figure 5 showing the Lidar system availability and in particular the data recovery rate at each of the eleven (11) measurement heights. The already mentioned system availability of 100 % is – by definition – the same for all heights (white bars). The total data availability (blue bars) between the lowest (21 m) and the highest (201 m) measurement level is above 85 %.

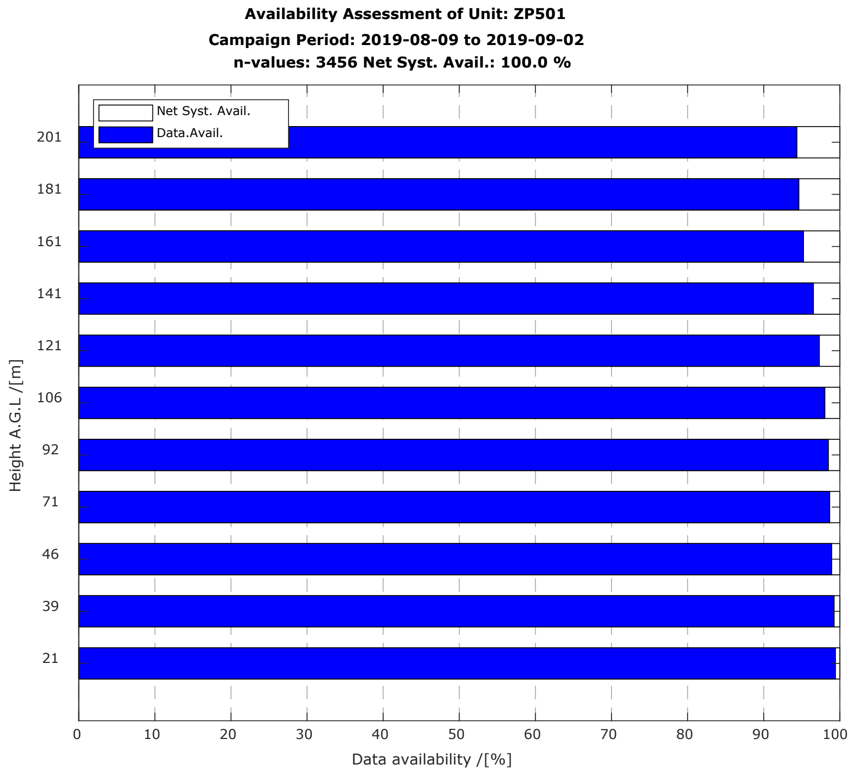


Figure 5: Lidar system and data availabilities for all measurement levels.

4.3 Data filtering

The data from both the Lidar and the mast were filtered for external parameters:

- wind direction to avoid non-valid wind speed sectors being influenced by e.g. mast wake effects, compare section 3.2,
- wind speed, clipping wind speeds below 3 m/s and
- temperatures below 0.2 °C.

After the application of those filters the number of ten-minute data points remaining to be processed was reduced to a percentage between 76.8 % at 21 m and 89.2 % at 92 m, compare Table 5.

4.4 Wind speed comparison

Cup anemometers are regarded as the current industry standard for wind speed measurements at wind farm sites. Measurements with cup anemometers must therefore be considered the standard reference against which any new measurement device needs to be judged.

Wind speed as treated in this LPV process are assessed by means of Linear Regressions through the origin of the form

$$y = m\,x + b \text{ and } \quad b{=}{:}0$$

between Lidar (y-axis) wind speeds and cup (x-axis) wind speeds for the four mentioned height levels were derived from the comparison of data from the following wind speed ranges

a) all above 3 m/s
b) 4 to 16 m/s [1]

according to the following acceptance criteria

1) slope (m) (**KPI** X_{mws}) between 0.98 and 1.02 for all WS ranges a) and b)
2) $R^2 > 0.97$ (**KPI** R^2_{mws}) for all WS ranges a) and b)

as prescribed in and Appendix A.

This campaign represents a series performance test of a technology proven Remote Sensing device. As the test campaign was limited in WS coverage for natural reasons, the core verification concentrates on a subset of statistically meaningful performance criteria (in terms of amount of available representative data) being treated relevant for acceptance.

[1] In consistency with the IEC bin selection criteria the actual range spans from 3.75 to 16.25 since 4 m/s and 16 m/s are the central points of the corresponding 0.5 m/s wide bins.

Results of wind speed comparisons

The time series of wind speeds measured by the Lidar (for all 4 pre-set heights) covering 24 days is overlapped by the met mast own measurements. Two comparison heights (21 m and 92 m) are shown in Appendix C.

Table 6 summarizes the wind speed regression results for all four (4) comparison heights showing that the ZX Lidar at hand achieves a high level of accuracy compared to the respective cups in terms of regression slopes (m) which are close to unity and good regression coefficient R^2 (**KPI** R^2_{mws}). Figure 6 shows the corresponding regression plots for the wind speed range >= 3 m/s (upper row out of 4).

The mean Lidar wind speeds as averaged over all used values (**KPI** C_{mwsd}) resemble those of the cups closely (see columns 5 and 6 of Table 6), yielding a very good relative Campaign Mean WS Differences (**KPI** C_{mwsd}) at all assessed measurement heights for both WS ranges.

Table 7 reflects the results according to the absolute wind speed error criterion. It shows that for the wind speed range 4 to 16 m/s at all height levels between 21 to 92 m a fraction of 1.6 to 2.5 % of concurrent 10-minute data points exceed the prescribed wind speed difference threshold of 0.5 m/s which is below the allowed upper limit of 10 %.

With respect to the linear WS regressions, the following KPI's Acceptance Criteria are passed

- ✓ The Best Practice Acceptance Criterion for slope (**KPI** X_{mws}) to be between 0.98 and 1.02 is successfully passed at all treated levels and for all WS ranges.
- ✓ The Best Practice Acceptance Criterion for R^2 (**KPI** R^2_{mws}) to be > 0.98 is successfully passed at all treated levels and for all WS ranges.
- ✓ The Best Practice Acceptance Criterion for the relative Campaign Mean Wind Speed Difference (**KPI** C_{mwsd}) (see Table 6, column 8) is successfully passed at all treated levels and in both WS ranges.

Furthermore, the following wind speed related Acceptance Criteria were met:

- ✓ The Acceptance Criterion for absolute Wind Speed Difference (**KPI** A_{wsd}) is successfully passed at all treated levels (see Table 7).

92 m level	# values	slope	R^2	WS-avg Cup	WS-avg LiDAR	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{mws}				KPI C_{mwsd}
All >= 3 m/s	3084	0.998	0.994	7.51	7.48	-0.027	-0.35%
4 - 16 m/s	2858	0.999	0.992	7.72	7.70	-0.024	-0.31%

71 m level	# values	slope	R^2	WS-avg Cup	WS-avg LiDAR	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{mws}				KPI C_{mwsd}
All >= 3 m/s	3035	0.998	0.995	7.10	7.07	-0.024	-0.33%
4 - 16 m/s	2784	0.998	0.994	7.37	7.35	-0.022	-0.29%

46 m level	# values	slope	R^2	WS-avg Cup	WS-avg LiDAR	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{mws}				KPI C_{mwsd}
All >= 3 m/s	2937	0.993	0.995	6.56	6.51	-0.052	-0.79%
4 - 16 m/s	2635	0.993	0.994	6.90	6.85	-0.052	-0.75%

21 m level	# values	slope	R^2	WS-avg Cup	WS-avg LiDAR	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{mws}				KPI C_{mwsd}
All >= 3 m/s	2655	1.001	0.993	5.95	5.95	0.000	0.00%
4 - 16 m/s	2242	1.002	0.991	6.42	6.43	0.006	0.09%

Table 6: Regression results for comparison; acceptance relevant results are colour shaded.

Criterion for abs WS error	> 0.5 m/s for 4 to 16 m/s KPI A_{wsd}		
Height Level	total #	identified #	fraction
92 m	2797	71	2.54%
71 m	2715	48	1.77%
46 m	2512	40	1.59%
21 m	2125	45	2.12%

Table 7: Summary of absolute wind speed differences between cups and Lidar.

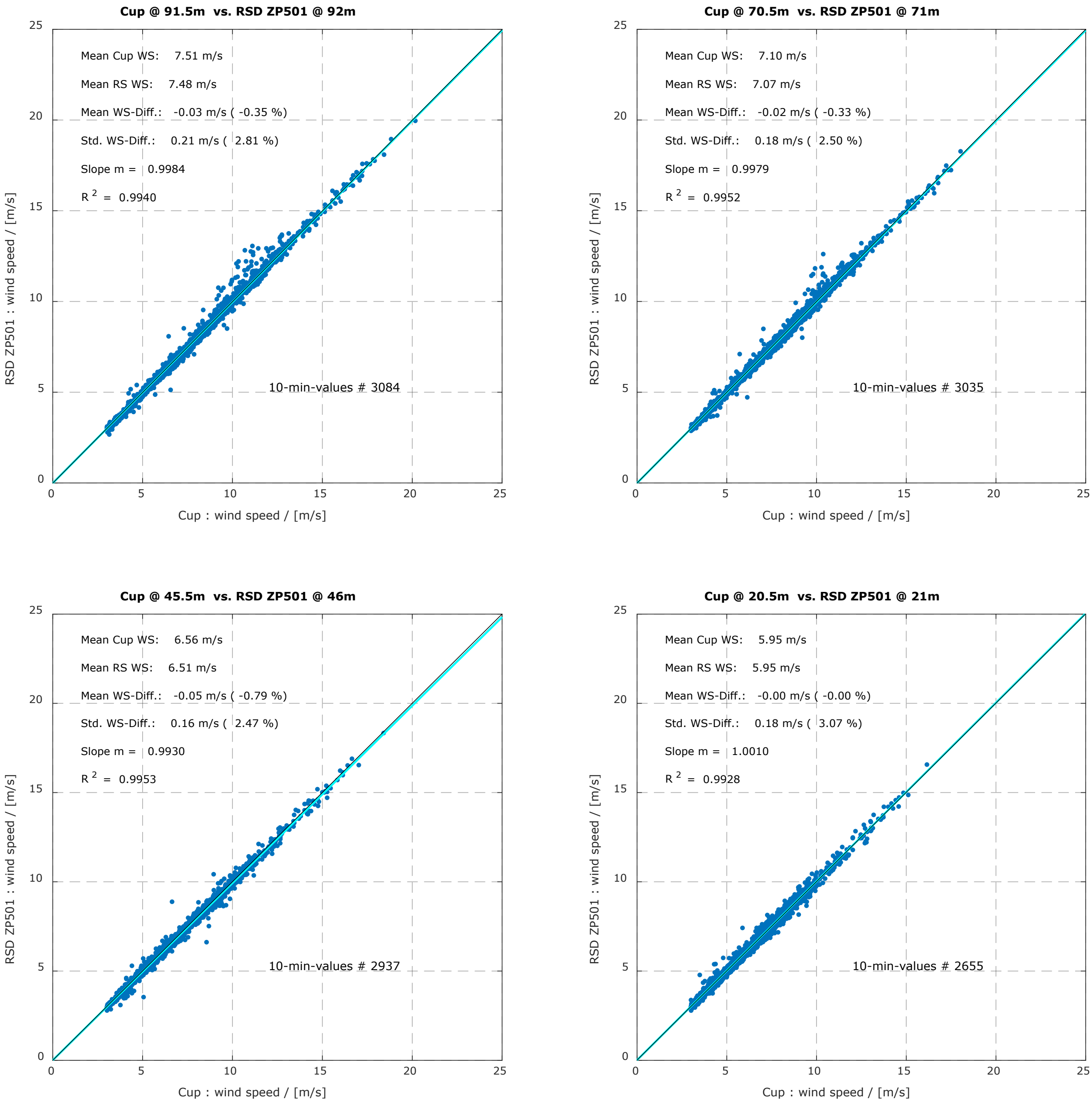


Figure 6: Plots of linear wind speed regression results for 21, 46, 71 and 92 m

4.5 Wind direction comparison

By comparing the wind direction as measured by the Lidar device at its 88 m level with the mast mounted ultrasonic anemometer at 88 m A.G.L., it is possible to see how well correlated the measures are, providing confidence in that the Lidar is 'seeing' the same wind direction as the vane. In order to validate this comparison quantitatively a two variant regression solving for the slope m and the interception of the best-fit line with the y-axis b (according to y = m x + b) was performed, compare Appendix A.

The results of such regression are shown in the x-y-plots in Figure 7 with the sonic/vane wind direction at 88 and 43.5 m on the x-axis and the Lidar direction at 88 and 46 m on the y-axis. For this analysis the data were again filtered for Lidar and the cup wind speeds at 92 m, i.e. for WS >=3 m/s (to avoid false readings from the sonic/vane at low wind speeds), but not for possibly disturbed wind directions sectors.

Note that a few 180° wind direction ambiguities were observed, when ZP300 Lidar data were correlated to the 3D ultrasonic anemometer readings at 88 m and wind vane at 43.5 m (see Appendix D). These ambiguities were solved using mast vane wind directions at the same heights as reference for correction. This mast based correction is justified by the assumption, that the few 180° misreading occurrences are related to lower wind speed in combination with near ground site induced turbulences. Time series of wind direction present during the course of the campaign together with raw data correlations and WD distribution statistics can be found in Appendix D.

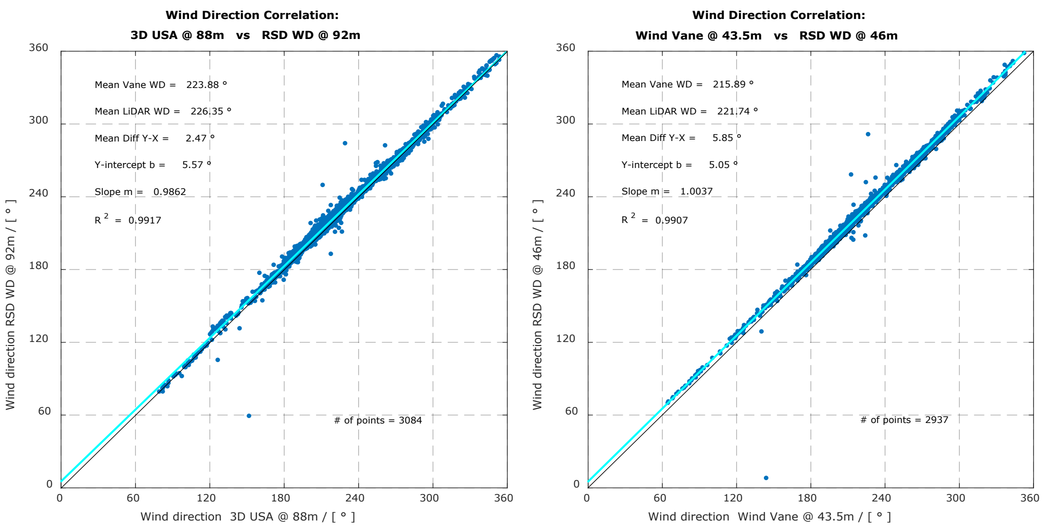


Figure 7: Regression plot of wind direction comparisons at 88 m (left) and 43.5 m (right)

The regression plots in Figure 7 reveal a close resemblance between Lidar and sonic/vane wind direction measures for both heights at 88 m and 43.5 m with an offset (in terms of a mean difference) of 2.5° and 5.8° which is within typical directional setup uncertainties for wind vanes/sonic and remotes sensing devices. Table 8 summarizes the WD comparison results for the acceptance relevant WD comparison levels at 88.0 and 43.5 m, showing an equally good resemblance slope.

WS filtering for WS > 3 m/s				
Height level	**# values**	**slope**	**offset [°]**	**R^2**
[m]	[-]	**KPI X_{mwd}**	**KPI OFF_{mwd}**	**KPI R^2_{mwd}**
88	3084	0.986	2.472	0.992
43.5	2937	1.004	5.847	0.991

Table 8: Summary of WD comparison results for both comparison levels

✓ The Acceptance Criteria for the respective KPIs for wind direction assessment (**KPIs** for X_{mwd}, OFF_{mwd}, and R^2_{mwd}) are passed for both (43.5 and 88.0 m) assessment levels.

4.6 Performance verification according to revised IEC standard, Annex L

This subsection represents as a supplement to the standard Lidar DNV GL / NORSEWInD performance verification test with respect to a RSD validation approach as described in the latest edition of the IEC standard for power performance tests [3]. This approach is based on a wind speed bin averaged procedure in order to compare the horizontal wind speed measurements acquired by the RSD and the reference sensors at the mast. The objective of the IEC approach is to calculate the bin-wise deviation of the two sources and report the associated uncertainty.

The bin averaging procedure was performed using 0.5 m/s wide wind speed bins centred on integers of from 4 to 16 m/s. In order to achieve statistic relevance this IEC approach requires

- a minimum of three (3) 10-minunte values available within each wind speed bin and
- a total amount of 180 hours of valid data (corresponding to a number of 1080 10-min values)

Figures 8 to 11 show scatter plots of the wind speed comparison based on 10 min averages between the data pairs of the Lidar and the cups at 21 m, 46 m, 71 m and 92 m, respectively. In addition, the 10-minute averaged deviation for each data point of the two data sets is plotted (red dots).

Furthermore, the correlation coefficient, mean deviation and standard deviation of the deviations are shown in Table 9. The relative deviation of the data pairs was calculated in relation to the cup wind speeds as reference.

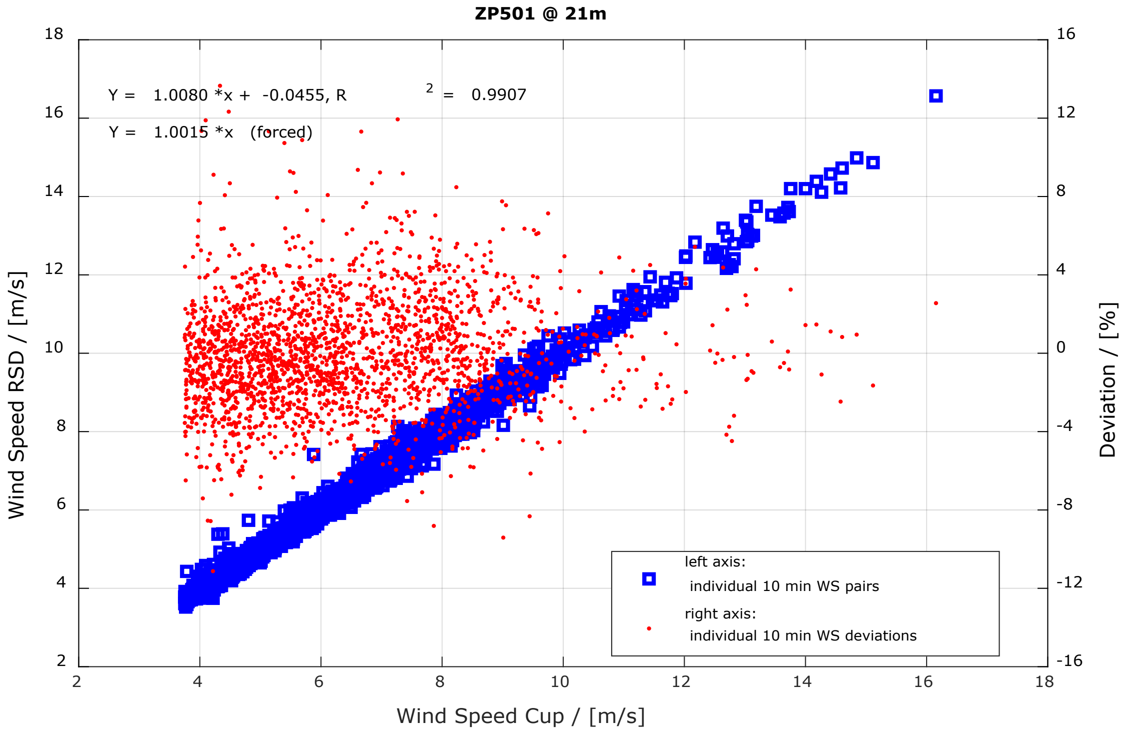


Figure 8: Comparison of the horizontal wind speed component at 21 m

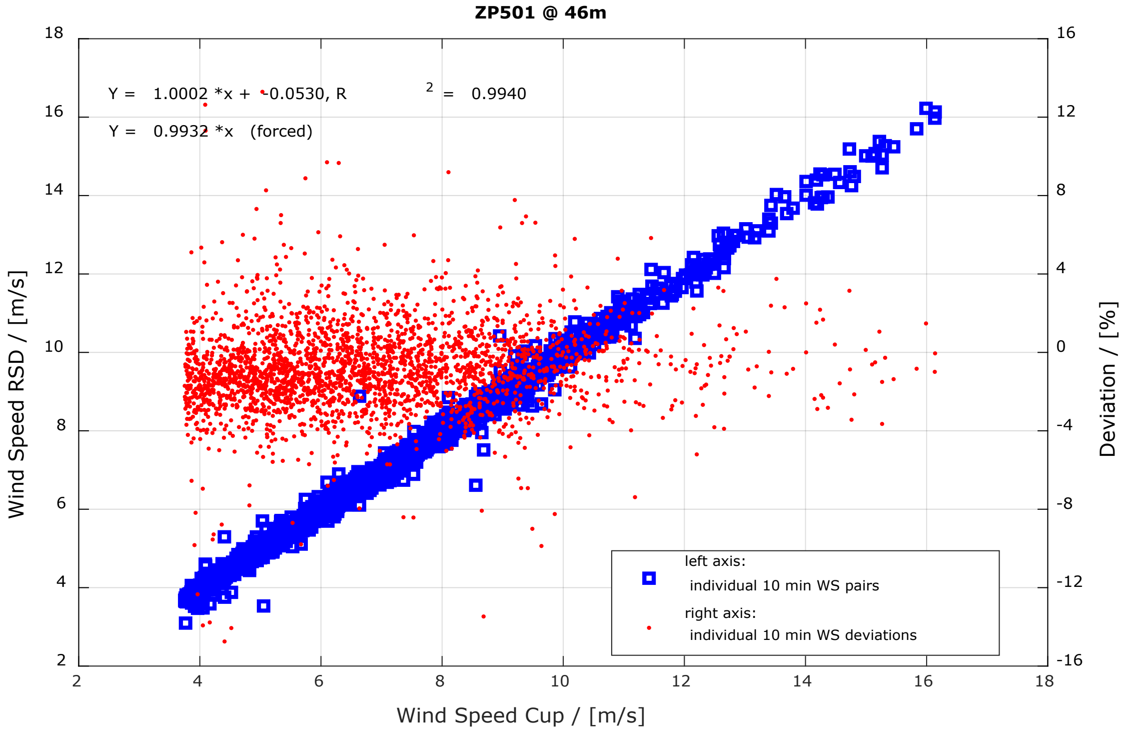


Figure 9: Comparison of the horizontal wind speed component at 46 m

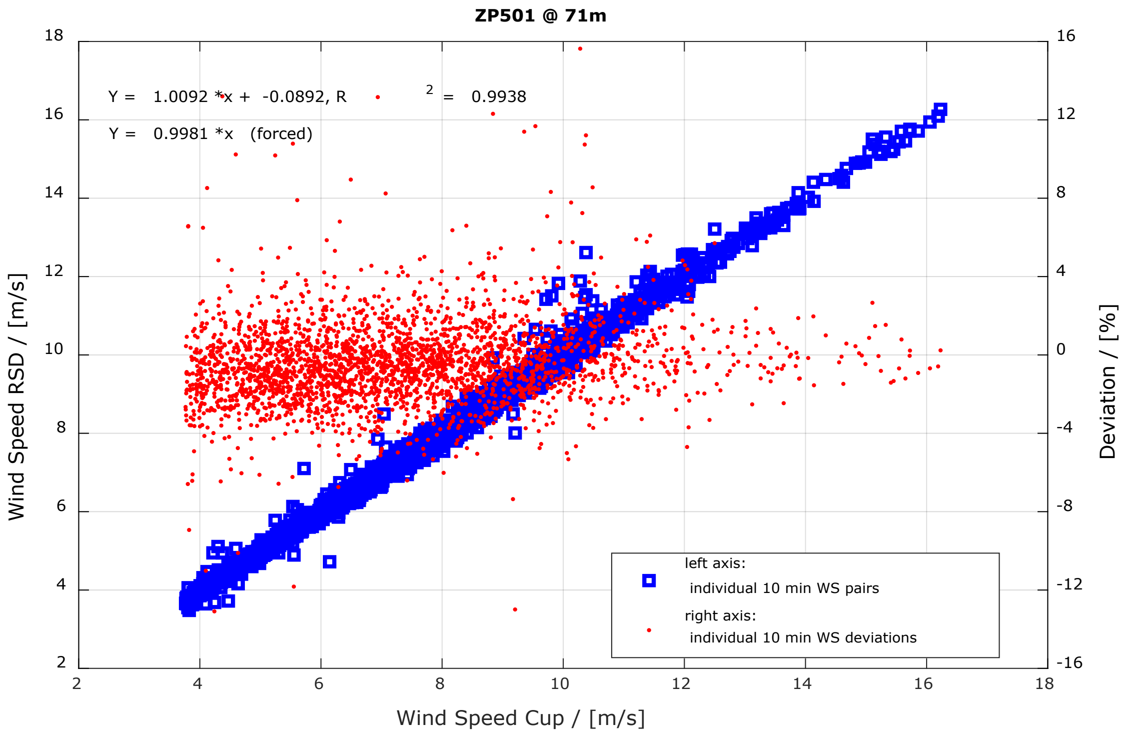


Figure 10: Comparison of the horizontal wind speed component at 71 m

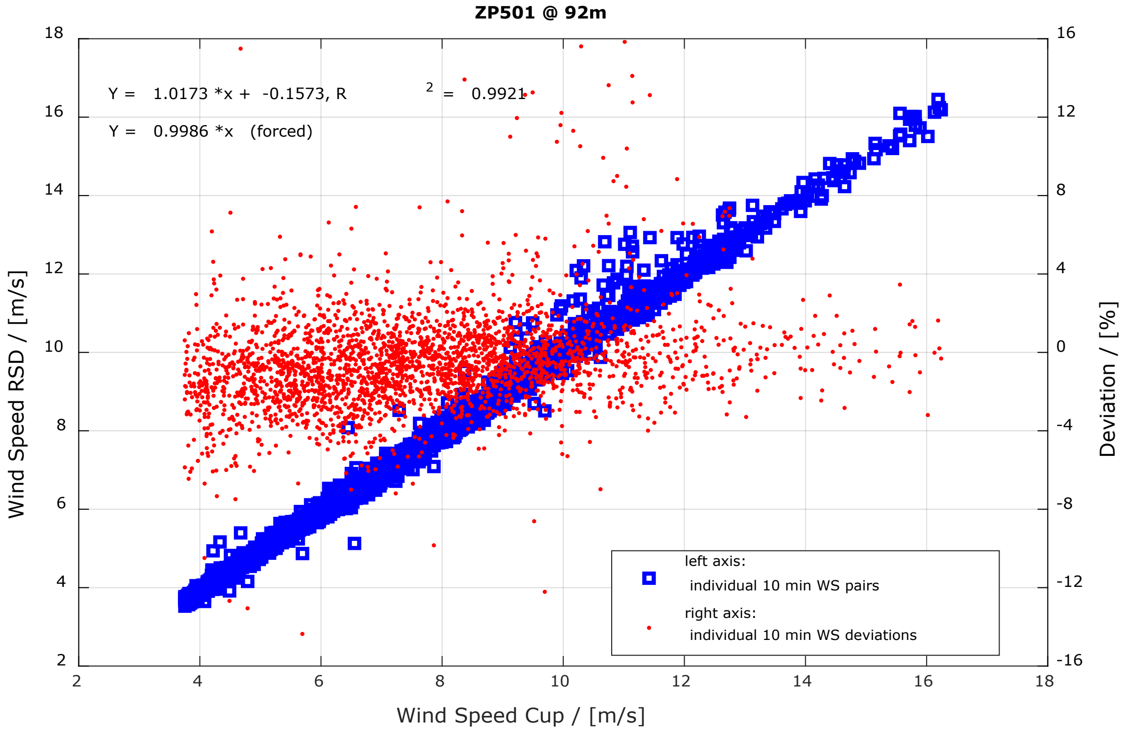


Figure 11: Comparison of the horizontal wind speed component at 92 m

Height level	Coefficient of Determination	Mean Deviation		STD of Deviations	Data Points
[m]	(R^2)	[m/s]	[%]	[%]	#
92	0.9921	-0.02	-0.50%	2.62%	2858
71	0.9938	-0.02	-0.40%	2.42%	2784
46	0.9940	-0.05	-0.83%	2.48%	2635
21	0.9907	0.01	0.02%	2.98%	2242

Table 9: Statistical parameters of wind speed deviation

4.6.1 Performance verification uncertainty

Bin-averaged wind speeds of the RSD and the reference measurements are shown in Figures 12 to 15. The bin-averaged deviation (solid red line in the graphs) can be compared to the standard uncertainty of the cup anemometers combined with the statistical uncertainty of the comparison for each of the WS bins.

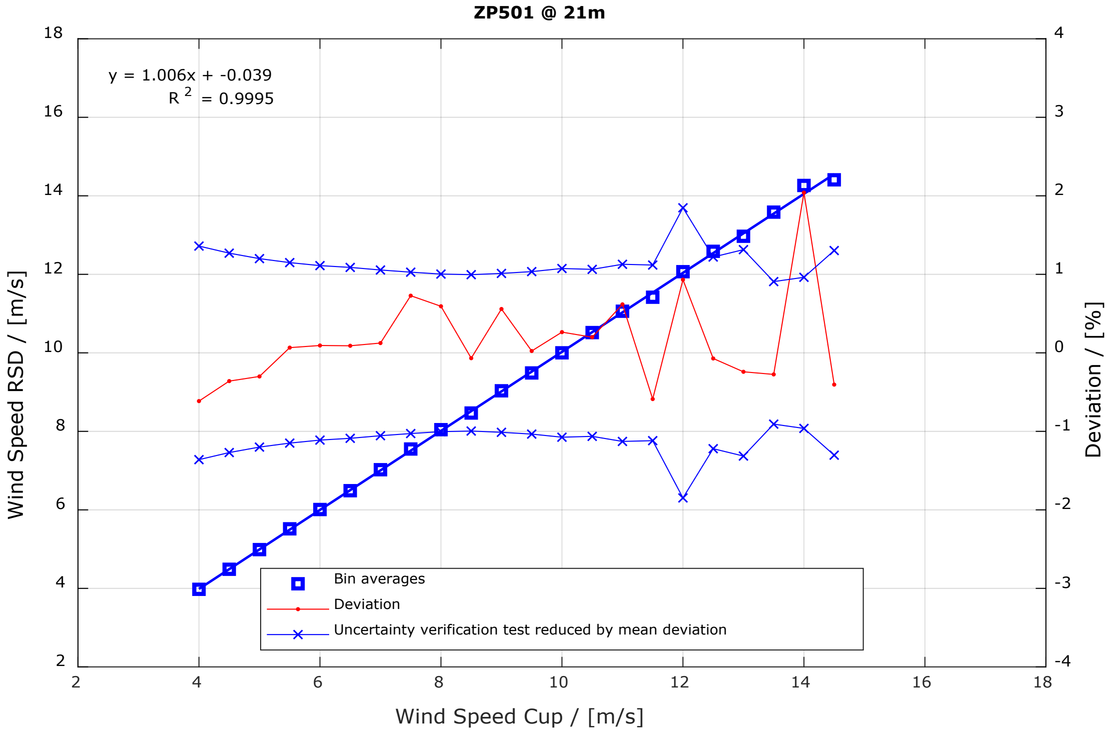


Figure 12: Bin-wise comparison of the horizontal wind speed component at 21 m

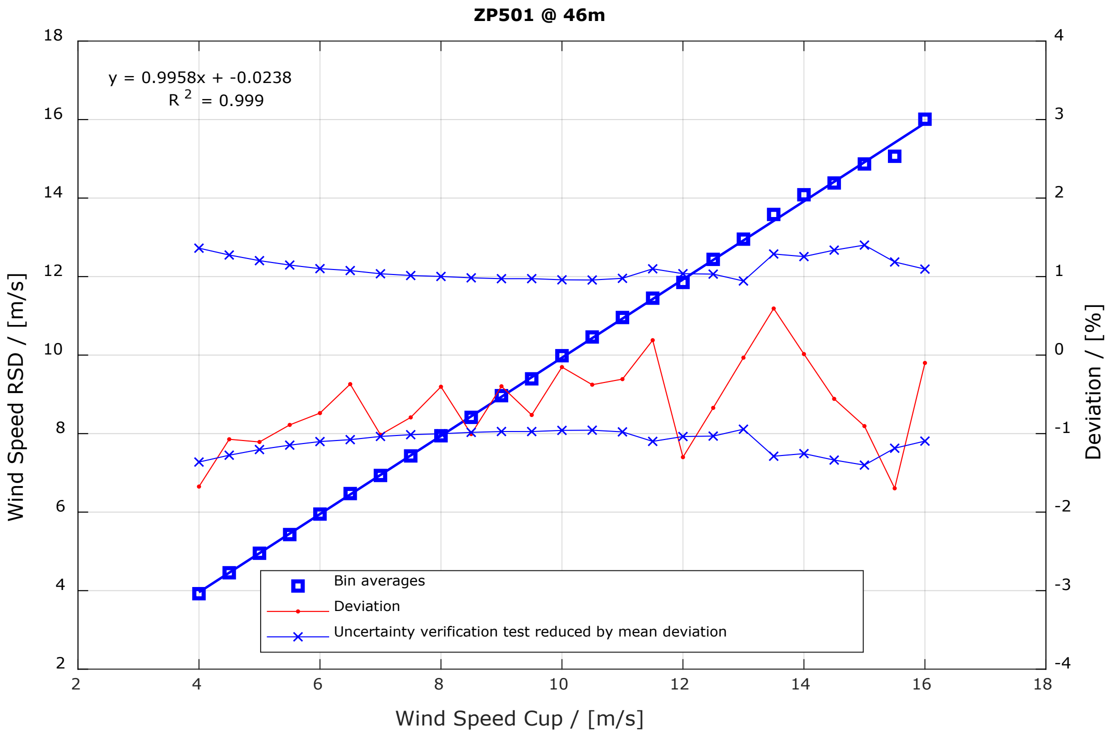


Figure 13: Bin-wise comparison of the horizontal wind speed component at 46 m

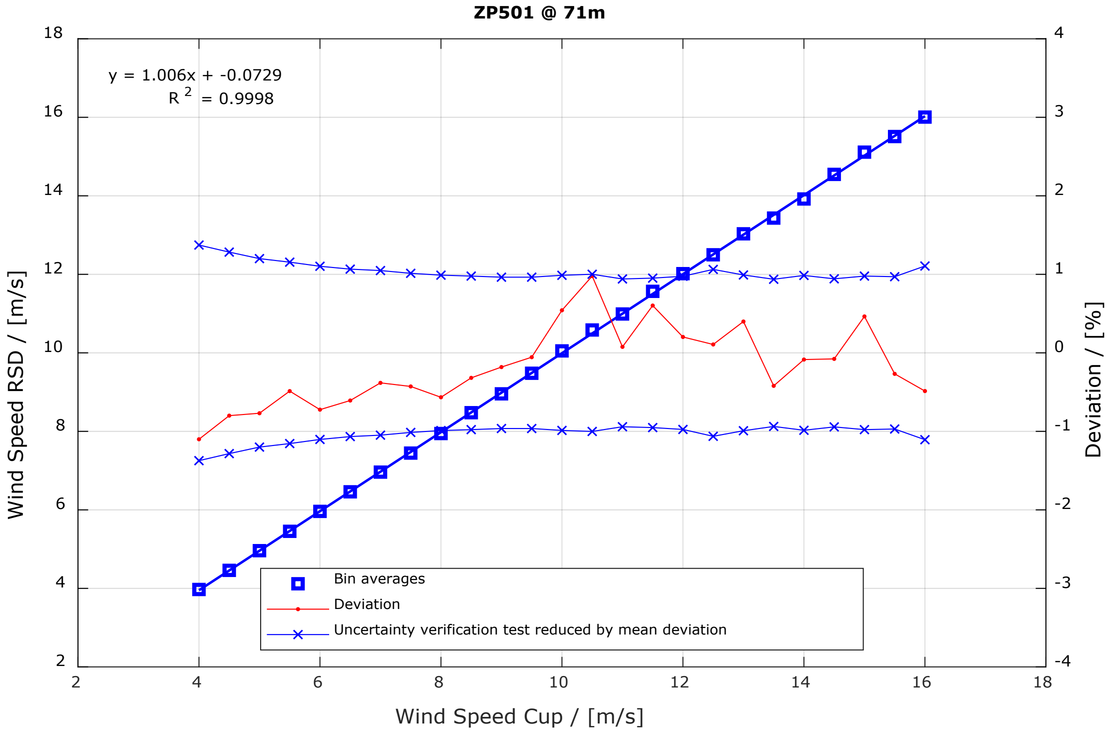


Figure 14: Bin-wise comparison of the horizontal wind speed component at 71 m

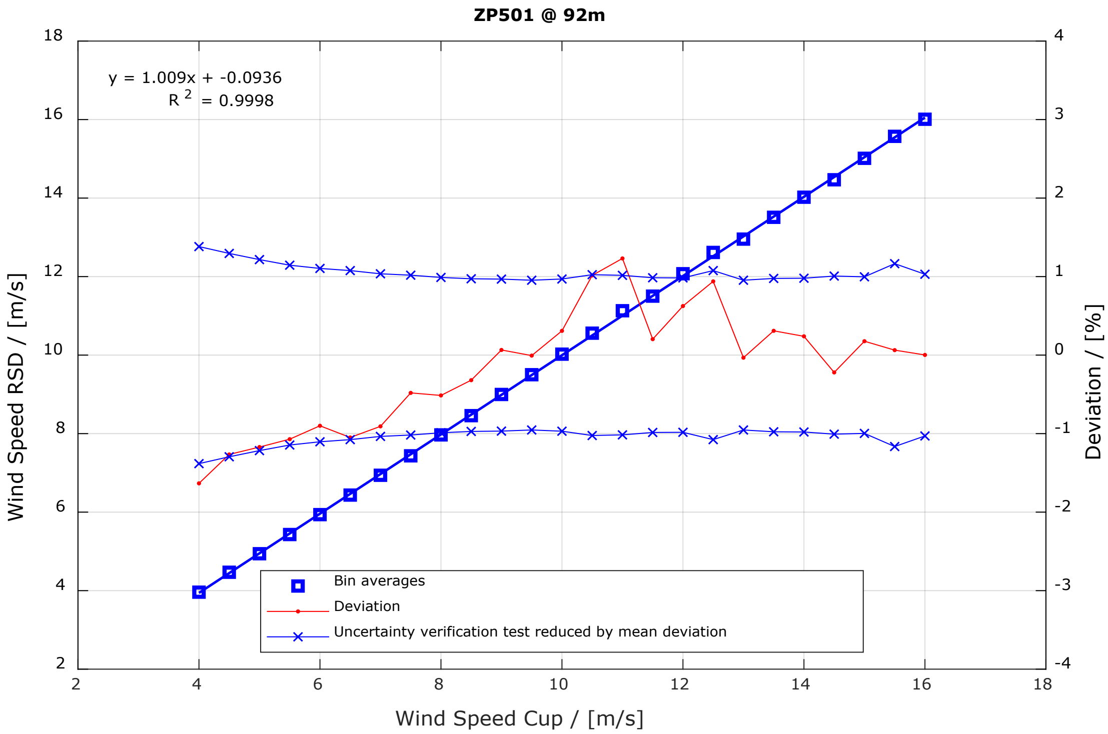


Figure 15: Bin-wise comparison of the horizontal wind speed component at 92 m

According to the IEC standard the verification uncertainty consists of five independent uncertainty components, which are summarized below:

1. Reference / anemometer uncertainty
2. Mean deviation of the remote sensor measurements and the reference measurements
3. Standard uncertainty of the measurement of the remote sensing device
4. Mounting uncertainty of the remote sensor at the verification test
5. Uncertainty due to non-homogenous flow

The different uncertainty components are added in quadrature for each wind speed bin. The uncertainty due to non-homogenous flow between the measurement volume of the Lidar and at the met mast is assumed to be negligible due to the proximity of the Lidar to the mast and the benign terrain conditions at the Remote Sensing Test Site. Details on the calculation of the separate uncertainty components are described in Appendix F.

The results of the uncertainty calculation for the IEC compliant verification of the Lidar device at every comparison level are plotted in Figures 12 to 15. The finally combined uncertainties of the remote sensing RSD (V_{RSD}) for the different WS bins and comparison levels show results values well below 2 % within most of the bins.

For the current Lidar verification campaign the completeness requirement to yield 180 hours of valid and useable concurrent data (which translates into 7.5 days of data) in the WS range 4 and 16 m/s between the RSD and the reference cup is met for each comparison level.

The additional requirement of yielding a minimum of 3 data pairs in each 0.5 m/s wind speed bin in the same WS range is fulfilled for most of bins and comparison levels, however, with exceptions at bin centre 15.0 m/s and greater at 21 m.

In Appendix G, the environmental parameters - present during the performance verification test - are shown.

Height level 21m												
BIN lower [m/s]	BIN upper [m/s]	# of 10 min data sets	V_{rsd} [m/s]	V_{mm} [m/s]	V_{maxrsd} [m/s]	V_{minrsd} [m/s]	Std_{Vrsd} [m/s]	$Std_{Vrsd}/\sqrt{n}$ [m/s]	Mean deviation [%]	RSD Mounting uncertainty [%]	V_{cup} Uncertainty [%]	**V_{RSD} Uncertainty (k=1) [%]**
3.75	4.25	240	3.98	4.00	4.61	3.52	0.19	0.012	-0.61%	0.50%	1.23%	**1.50%**
4.25	4.75	260	4.49	4.50	5.39	4.05	0.20	0.012	-0.36%	0.50%	1.14%	**1.32%**
4.75	5.25	251	4.99	5.00	5.74	4.54	0.19	0.012	-0.30%	0.50%	1.07%	**1.24%**
5.25	5.75	236	5.52	5.51	6.31	5.07	0.21	0.014	0.07%	0.50%	1.01%	**1.15%**
5.75	6.25	224	6.01	6.00	7.42	5.51	0.23	0.015	0.09%	0.50%	0.96%	**1.12%**
6.25	6.75	171	6.49	6.48	7.42	5.92	0.25	0.019	0.09%	0.50%	0.93%	**1.10%**
6.75	7.25	160	7.02	7.01	7.74	6.51	0.25	0.020	0.12%	0.50%	0.89%	**1.07%**
7.25	7.75	164	7.55	7.50	8.13	6.86	0.25	0.019	0.73%	0.50%	0.86%	**1.26%**
7.75	8.25	168	8.04	8.00	8.93	7.17	0.25	0.019	0.59%	0.50%	0.84%	**1.17%**
8.25	8.75	128	8.47	8.47	9.14	7.94	0.26	0.023	-0.07%	0.50%	0.82%	**1.00%**
8.75	9.25	72	9.03	8.98	9.74	8.16	0.29	0.034	0.56%	0.50%	0.80%	**1.16%**
9.25	9.75	55	9.49	9.49	10.18	8.66	0.33	0.044	0.02%	0.50%	0.78%	**1.04%**
9.75	10.25	24	10.00	9.97	10.52	9.49	0.28	0.057	0.26%	0.50%	0.77%	**1.11%**
10.25	10.75	17	10.52	10.50	11.06	9.94	0.25	0.060	0.20%	0.50%	0.76%	**1.09%**
10.75	11.25	18	11.06	10.99	11.63	10.58	0.33	0.077	0.62%	0.50%	0.74%	**1.29%**
11.25	11.75	12	11.42	11.48	11.95	10.97	0.28	0.080	-0.59%	0.50%	0.74%	**1.27%**
11.75	12.25	7	12.07	11.96	12.84	11.47	0.53	0.199	0.93%	0.50%	0.73%	**2.09%**
12.25	12.75	9	12.59	12.60	13.19	12.17	0.33	0.109	-0.07%	0.50%	0.71%	**1.23%**
12.75	13.25	11	12.97	13.00	13.75	12.21	0.43	0.131	-0.24%	0.50%	0.71%	**1.35%**
13.25	13.75	5	13.58	13.62	13.72	13.48	0.09	0.041	-0.27%	0.50%	0.70%	**0.95%**
13.75	14.25	3	14.26	13.98	14.39	14.20	0.11	0.062	2.04%	0.50%	0.70%	**2.26%**
14.25	14.75	4	14.41	14.47	14.73	14.11	0.29	0.145	-0.40%	0.50%	0.69%	**1.38%**
14.75	15.25	2										
15.25	15.75	0										
15.75	16.25	1										

Table 10: Uncertainty calculation for 21 m level

Height level 46m													
BIN lower [m/s]	BIN upper [m/s]	# of 10 min data sets	V_{rsd} [m/s]	V_{mm} [m/s]	V_{maxrsd} [m/s]	V_{minrsd} [m/s]	Std_{Vrsd} [m/s]	$Std_{Vrsd}/\sqrt{n}$ [m/s]	Mean deviation [%]	RSD Mounting uncertainty [%]	V_{cup} Uncertainty [%]	**V_{RSD} Uncertainty (k=1) [%]**
3.75	4.25	231	3.92	3.99	4.61	3.10	0.18	0.012	-1.67%	0.50%	1.23%	**2.16%**
4.25	4.75	203	4.46	4.50	5.30	3.76	0.19	0.013	-1.07%	0.50%	1.14%	**1.67%**
4.75	5.25	256	4.95	5.01	5.70	3.54	0.21	0.013	-1.11%	0.50%	1.07%	**1.64%**
5.25	5.75	243	5.43	5.48	6.25	5.05	0.18	0.011	-0.89%	0.50%	1.01%	**1.45%**
5.75	6.25	235	5.95	5.99	6.69	5.47	0.18	0.012	-0.74%	0.50%	0.96%	**1.33%**
6.25	6.75	233	6.47	6.50	8.88	5.95	0.25	0.016	-0.37%	0.50%	0.92%	**1.14%**
6.75	7.25	216	6.93	7.01	7.46	6.41	0.19	0.013	-1.01%	0.50%	0.89%	**1.45%**
7.25	7.75	187	7.43	7.49	7.98	6.74	0.19	0.014	-0.79%	0.50%	0.86%	**1.29%**
7.75	8.25	148	7.95	7.98	8.85	7.57	0.22	0.018	-0.40%	0.50%	0.84%	**1.08%**
8.25	8.75	176	8.41	8.50	8.95	6.62	0.26	0.020	-1.01%	0.50%	0.82%	**1.41%**
8.75	9.25	145	8.97	9.00	10.42	8.42	0.27	0.023	-0.40%	0.50%	0.80%	**1.05%**
9.25	9.75	102	9.40	9.47	10.17	8.64	0.28	0.028	-0.76%	0.50%	0.79%	**1.24%**
9.75	10.25	78	9.98	10.00	10.78	9.05	0.25	0.029	-0.15%	0.50%	0.77%	**0.97%**
10.25	10.75	50	10.46	10.50	10.92	9.99	0.23	0.033	-0.38%	0.50%	0.76%	**1.03%**
10.75	11.25	34	10.96	10.99	11.42	10.36	0.26	0.044	-0.31%	0.50%	0.74%	**1.03%**
11.25	11.75	17	11.45	11.43	12.12	10.96	0.31	0.075	0.19%	0.50%	0.74%	**1.12%**
11.75	12.25	17	11.85	12.01	12.42	11.44	0.28	0.067	-1.30%	0.50%	0.72%	**1.67%**
12.25	12.75	20	12.44	12.52	13.04	11.98	0.31	0.070	-0.67%	0.50%	0.72%	**1.24%**
12.75	13.25	8	12.95	12.96	13.15	12.72	0.14	0.049	-0.03%	0.50%	0.71%	**0.95%**
13.25	13.75	7	13.58	13.50	14.03	13.10	0.35	0.132	0.59%	0.50%	0.70%	**1.43%**
13.75	14.25	7	14.08	14.08	14.55	13.68	0.35	0.131	0.01%	0.50%	0.69%	**1.26%**
14.25	14.75	8	14.38	14.47	15.19	13.95	0.43	0.152	-0.56%	0.50%	0.69%	**1.47%**
14.75	15.25	6	14.87	15.01	15.38	14.25	0.42	0.170	-0.90%	0.50%	0.68%	**1.69%**
15.25	15.75	4	15.07	15.33	15.27	14.71	0.26	0.130	-1.70%	0.50%	0.69%	**2.09%**
15.75	16.25	4	16.01	16.03	16.23	15.70	0.23	0.114	-0.10%	0.50%	0.67%	**1.11%**

Table 11: Uncertainty calculation for 46 m level

Height level 71m												
BIN lower [m/s]	BIN upper [m/s]	# of 10 min data sets	V_{rsd} [m/s]	V_{mm} [m/s]	V_{maxrsd} [m/s]	V_{minrsd} [m/s]	Std_{Vrsd} [m/s]	$Std_{Vrsd}/\sqrt{n}$ [m/s]	Mean deviation [%]	RSD Mounting uncertainty [%]	V_{cup} Uncertainty [%]	**V_{RSD} Uncertainty (k=1) [%]**
3.75	4.25	156	3.97	4.02	4.95	3.48	0.19	0.015	-1.10%	0.50%	1.23%	**1.77%**
4.25	4.75	167	4.46	4.50	5.11	3.72	0.19	0.015	-0.80%	0.50%	1.14%	**1.52%**
4.75	5.25	208	4.96	5.00	5.78	4.60	0.17	0.012	-0.77%	0.50%	1.07%	**1.43%**
5.25	5.75	234	5.45	5.48	7.10	4.90	0.21	0.014	-0.49%	0.50%	1.01%	**1.26%**
5.75	6.25	238	5.96	6.00	6.56	4.72	0.20	0.013	-0.72%	0.50%	0.96%	**1.32%**
6.25	6.75	245	6.46	6.50	7.07	5.86	0.20	0.013	-0.61%	0.50%	0.92%	**1.23%**
6.75	7.25	194	6.96	6.99	8.49	6.51	0.24	0.017	-0.38%	0.50%	0.89%	**1.12%**
7.25	7.75	227	7.45	7.48	8.09	6.91	0.20	0.013	-0.43%	0.50%	0.86%	**1.10%**
7.75	8.25	215	7.94	7.99	8.69	7.43	0.20	0.013	-0.57%	0.50%	0.84%	**1.14%**
8.25	8.75	180	8.48	8.50	9.04	7.90	0.23	0.017	-0.32%	0.50%	0.82%	**1.03%**
8.75	9.25	173	8.96	8.97	9.93	8.01	0.23	0.018	-0.18%	0.50%	0.80%	**0.98%**
9.25	9.75	150	9.48	9.49	11.42	8.97	0.30	0.025	-0.06%	0.50%	0.78%	**0.97%**
9.75	10.25	98	10.05	10.00	11.83	9.47	0.37	0.038	0.54%	0.50%	0.77%	**1.13%**
10.25	10.75	80	10.58	10.48	12.61	10.06	0.41	0.045	0.98%	0.50%	0.76%	**1.40%**
10.75	11.25	60	10.99	10.98	11.87	10.52	0.25	0.032	0.08%	0.50%	0.75%	**0.95%**
11.25	11.75	41	11.57	11.50	12.13	10.93	0.26	0.040	0.60%	0.50%	0.73%	**1.13%**
11.75	12.25	36	12.02	11.99	12.58	11.48	0.31	0.051	0.20%	0.50%	0.73%	**1.00%**
12.25	12.75	15	12.50	12.48	13.21	12.00	0.30	0.077	0.11%	0.50%	0.72%	**1.08%**
12.75	13.25	15	13.03	12.98	13.50	12.65	0.25	0.064	0.40%	0.50%	0.71%	**1.07%**
13.25	13.75	16	13.43	13.49	13.74	13.10	0.20	0.050	-0.42%	0.50%	0.70%	**1.03%**
13.75	14.25	10	13.92	13.93	14.41	13.73	0.22	0.069	-0.09%	0.50%	0.70%	**1.00%**
14.25	14.75	5	14.55	14.56	14.76	14.41	0.13	0.060	-0.08%	0.50%	0.69%	**0.95%**
14.75	15.25	9	15.11	15.04	15.51	14.89	0.22	0.075	0.46%	0.50%	0.68%	**1.08%**
15.25	15.75	8	15.51	15.55	15.76	15.19	0.21	0.076	-0.27%	0.50%	0.68%	**1.01%**
15.75	16.25	4	16.01	16.08	16.27	15.71	0.23	0.117	-0.49%	0.50%	0.67%	**1.21%**

Table 12: Uncertainty calculation for 71 m level

Height level 92m												
BIN lower [m/s]	BIN upper [m/s]	# of 10 min data sets	V_{rsd} [m/s]	V_{mm} [m/s]	V_{maxrsd} [m/s]	V_{minrsd} [m/s]	Std_{Vrsd} [m/s]	$Std_{Vrsd}/\sqrt{n}$ [m/s]	Mean deviation [%]	RSD Mounting uncertainty [%]	V_{cup} Uncertainty [%]	**V_{RSD} Uncertainty (k=1) [%]**
3.75	4.25	136	3.96	4.03	4.94	3.53	0.20	0.017	-1.63%	0.50%	1.22%	**2.15%**
4.25	4.75	134	4.47	4.53	5.40	3.92	0.21	0.018	-1.27%	0.50%	1.13%	**1.82%**
4.75	5.25	143	4.94	5.00	5.41	4.16	0.19	0.016	-1.17%	0.50%	1.07%	**1.69%**
5.25	5.75	223	5.43	5.49	5.95	4.88	0.17	0.011	-1.07%	0.50%	1.01%	**1.57%**
5.75	6.25	213	5.94	5.99	6.53	5.53	0.18	0.013	-0.90%	0.50%	0.96%	**1.43%**
6.25	6.75	223	6.43	6.50	8.08	5.13	0.24	0.016	-1.05%	0.50%	0.92%	**1.51%**
6.75	7.25	248	6.94	7.00	7.43	6.37	0.20	0.013	-0.91%	0.50%	0.89%	**1.38%**
7.25	7.75	213	7.43	7.47	8.52	6.84	0.22	0.015	-0.48%	0.50%	0.87%	**1.13%**
7.75	8.25	207	7.97	8.01	8.71	7.09	0.20	0.014	-0.51%	0.50%	0.84%	**1.12%**
8.25	8.75	230	8.46	8.48	9.54	8.02	0.21	0.014	-0.32%	0.50%	0.82%	**1.02%**
8.75	9.25	200	9.00	8.99	10.76	8.47	0.29	0.020	0.07%	0.50%	0.80%	**0.97%**
9.25	9.75	175	9.50	9.50	10.75	8.51	0.28	0.021	-0.01%	0.50%	0.78%	**0.95%**
9.75	10.25	123	10.02	9.99	12.09	9.47	0.36	0.032	0.31%	0.50%	0.77%	**1.02%**
10.25	10.75	86	10.56	10.45	12.82	9.87	0.47	0.051	1.02%	0.50%	0.76%	**1.44%**
10.75	11.25	87	11.13	10.99	13.06	10.47	0.50	0.054	1.23%	0.50%	0.74%	**1.60%**
11.25	11.75	51	11.50	11.48	12.93	10.89	0.36	0.050	0.20%	0.50%	0.74%	**1.01%**
11.75	12.25	46	12.07	12.00	12.97	11.44	0.36	0.054	0.62%	0.50%	0.73%	**1.17%**
12.25	12.75	32	12.62	12.50	13.68	12.15	0.45	0.080	0.94%	0.50%	0.72%	**1.43%**
12.75	13.25	28	12.95	12.96	13.75	12.43	0.27	0.052	-0.03%	0.50%	0.71%	**0.96%**
13.25	13.75	12	13.51	13.47	13.81	13.17	0.22	0.063	0.31%	0.50%	0.70%	**1.03%**
13.75	14.25	13	14.02	13.99	14.42	13.60	0.24	0.067	0.24%	0.50%	0.70%	**1.01%**
14.25	14.75	13	14.47	14.50	14.82	13.91	0.28	0.079	-0.22%	0.50%	0.69%	**1.04%**
14.75	15.25	6	15.01	14.99	15.33	14.83	0.20	0.080	0.18%	0.50%	0.69%	**1.02%**
15.25	15.75	7	15.57	15.56	16.10	15.20	0.34	0.127	0.06%	0.50%	0.68%	**1.17%**
15.75	16.25	9	16.01	16.01	16.45	15.51	0.29	0.097	0.00%	0.50%	0.67%	**1.04%**

Table 13: Uncertainty calculation for 92 m level

5 IMPORTANT REMARKS AND LIMITATIONS

Independently performed LPV of individual Lidar devices as reported in this document present a reasonable means to assure overall system integrity of the Lidar unit after manufacturing, and are meant to give an indication of the quality of wind data produced by the Lidar.

Furthermore, the IEC compliant bin-wise uncertainty implementation may serve as a traceable means to judge the uncertainty of the RSD as determined from a well-defined verification process.

Any statement given in the context of system integrity and data quality related results within this report are limited to the given test site conditions, to the prevailing atmospheric (in particular wind) conditions and to the specific Lidar configuration as selected for this LPV campaign.

6 CONCLUSION

Concurrent ZP300 Lidar and cup anemometer wind measurements were carried out at the UK Remote Sensing Test Site to validate Lidar wind data quality against a well-known high quality standard cup anemometer. Measurement heights of 20.5 m, 45.5 m, 70.5 m and 91.5 m were available for wind speed correlations (43.5/88m for wind direction correlation) between a proximate met mast and a ZP300 Lidar with the serial number ZP501. The duration of the validation was 24 days. The test period and wind data coverage is considered a bit low but still sufficient for the purpose of characterizing the wind data performance of the ZX Lidar in the context of a Lidar Performance Verification.

The overall system availability for the mentioned net campaign duration of 24 days was 100 %. The LPV data availability at the selected Lidar measurement levels 21 m, 46 m, 71 m and 92 m ranges between 98.5 and 99.4 %. These data availability figures are relative to the number of maximum possible ten-minute data points for the net duration of the campaign.

Wind speed (and direction) correlations were carried out for each of the four WS measurement heights (two for WD) mentioned above. The wind speeds of both Lidar and cup anemometers, at all treated heights, correlated well, showing a low level of scatter and an excellent resemblance of Lidar wind speeds to those of cups, in terms of linear regression slopes.

In summary, the following KPI related Acceptance Criteria are met:

- ✓ The Acceptance Criterion for System Availability (**KPI** SA_{CA}) to be ≥95 % is successfully passed.
- ✓ The Acceptance Criterion for Data Availability (**KPI** DA_{CA}) to be ≥90 % is successfully met at all assessment levels.
- ✓ The Best Practice Acceptance Criterion for slope (**KPI** X_{mws}) to be between 0.98 and 1.02 is successfully passed at all treated levels and for all WS ranges.
- ✓ The Best Practice Acceptance Criterion for R^2 (**KPI** R^2_{mws}) to be > 0.98 is successfully passed at all treated levels and for all WS ranges.
- ✓ The Best Practice Acceptance Criterion for the relative Campaign Mean Wind Speed Difference (**KPI** C_{mwsd}) (see Table 6, column 8) is successfully passed at all assessed levels for both WS ranges.
- ✓ The Acceptance Criterion for absolute Wind Speed Difference (**KPI** A_{wsd}) is successfully passed at all treated levels (see Table 7).
- ✓ The Acceptance Criteria for the respective KPIs for wind direction assessment (**KPIs** for X_{mwd}, OFF_{mwd}, and R^2_{mwd}) are successfully passed at both comparison levels.

The performance verification and uncertainty calculation has been carried out in accordance with the IEC standard yielding a traceable uncertainty measure. The following deviations from applicable IEC test conditions are reported:

Due to the lack of periods of higher wind speeds during the verification campaign some wind speed bins did not fulfil the criteria of having at least 3 concurrent data points, they are: at bin centre 15.0 m/s and greater at 21 m.

In summary, this UK Remote Sensing Test Site validation campaign indicates that the ZP300 Lidar with the serial number ZP501 is able to reproduce cup anemometer wind speeds and wind directions at an accurate and acceptable level. DNV GL considers that the ZP300 Lidar device under test (with the S/N ZP501) can be used for formal wind potential and long-term wind resource assessments. Specifically, DNV GL concludes that this Lidar may be employed as a standalone measurement system – replacing a conventional met mast – given the following criteria are met:

(1) The Lidar is deployed in relatively simple terrain.

(2) In addition, it is considered good practice to ensure the long-term stability of the device through correlations with on-site masts or through the use of a post deployment performance verification campaign. It is noted that for compliance with TR6, a post deployment performance verification campaign is a requirement.

Finally, DNV GL recommends, that care needs to be taken with respect to the formal use of Lidar turbulence and extreme wind speed measures, not treated in this report but known to be different from classical anemometry measures. DNV GL likes to point out that good measurement and data collection practices need to be maintained for all wind speed measurements, be they Lidar or more conventional anemometry. Therefore, special care needs to be exercised in the transportation, installation and on-going maintenance of the Lidar as it may be exposed to a wide range of environmental conditions at different sites over time. A key element of any formal wind study is the traceability of the wind speed data uncertainty. Hence, a strict uncertainty assessment (which is not part of this report) should be employed. Furthermore, it is recommended that thorough practices of documenting the salient features of Lidar installation and maintenance are instigated from the outset.

7 REFERENCES

1. Wylie S, "*UK Remote Sensing Test Site: 91 m Mast Specification* ", by ZX Lidars., issued: 07/01/2019.

2. DNV GL, " *Best Practice Test and Verification Procedure for Wind Lidars on the Høvsøre Test Site",* GL GH-D Report WT 6960/09 for EU-Project NORSEWInD, Deliv. 1.1, June 2009

3. International Standard: IEC 61400-12-1: Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines. Ed. 2., Apr. 2017

4. IEA EXPERT GROUP STUDY ON RECOMMENDED PRACTICES FOR WIND TURBINE TESTING AND EVALUATION 11. WIND SPEED MEASUREMENT AND USE OF CUP ANEMOMETRY, 1. EDITION 1999

5. MEASNET: "Cup Anemometer Calibration Procedure". Version 1, September 1997

6. DNV GL. "Technical Note of Inspection of ZephIR's Reference Met Mast and Lidar Test Site (exec. 2018-04-18) at the UK Remote Sensing Test Site near Pershore/Throckmorton, UK" DNV GL Report, No. GLGH-4270 18 14677 267-R-0024-B, 2018-07-17

8 GLOSSARY

The following table lists abbreviations and acronyms used in this report.

Abbreviation Acronym	Meaning
AC	Acceptance Criterion
a.g.l.	Above ground level
DNV GL	New company name, successor of legacy GL GH
IEC	International Electro-technical Commission
IEA	International Energy Agency
GH-D	GL Garrad Hassan Deutschland GmbH
KPI	Key Performance Indicator
LPV	Lidar Performance Verification
PAR	Performance Assessment Requirement
RSD	Remote Sensing Device
TFCA	Thies First Class Advanced (cup anemometer)
TI	Turbulence Intensity
WD	Wind direction
WS	Wind speed

APPENDIX A KEY PERFORMANCE INDICATORS AND ACCEPTANCE CRITERIA [2]

Table 14: List of KPIs and ACs relevant for System and Data Availability assessment

KPI	**Definition / Rationale**	**Acceptance Criteria** [1]
SA_{CA}	**System Availability** The Lidar system is ready to function according to specifications and to deliver data, taking into account all time stamped data entries in the output data files including flagged data (e.g. by NaNs or 9999s) for the pre-defined total campaign length. The System Availability is the number of these time stamped data entries relative to the maximum possible number of data entries (for 10 minute intervals) within the pre-defined total campaign period. (Any conditions affecting the test's data availability outside of the LIDAR system's control is not to be included in this calculation. Such as: power outages, acts of nature causing system damage, communication outages, maintenance, etc.)	≥95%
DA_{CA}	**Data Availability** The Data Availability is defined as the number of valid data points returned by the Lidar unit as compared to maximum number of possible points that can be acquired during the test (Any conditions affecting the test's data availability outside of the LIDAR system's control is not to be included in this calculation. Such as: power outages, acts of nature causing system damage, communication outages, maintenance, etc.)	≥90%

1 Acceptance Criteria across total campaign duration

Table 15: List of KPIs and ACs relevant for Wind Data Accuracy assessment

KPI	Definition / Rationale	Acceptance Criteria [1]	
		Best Practice	Minimum
C_{mwsd}	**Campaign Mean Wind Speed – Difference** Absolute difference of mean wind speeds between Lidar and reference as measured over the whole verification campaign duration, expressed as percentage relative to the Campaign Mean Wind Speed A threshold is imposed on the Difference. Analysis shall be applied to wind speed ranges a) all above 3 m/s b) 4 to 16 m/s given achieved data coverage requirements	< 1 %	1 – 1.5 %
A_{wsd}	**Absolute Wind Speed Differences** Absolute 10 minute mean wind speed differences between Lidar and reference for all data points treated after filtering. A threshold is imposed on the Difference. Analysis shall be applied to wind speed ranges • 4 to 16 m/s given achieved data coverage requirements.	a) < 0.5 m/s b) within 5% Not more than 10% of data to exceed the criteria above.	
X_{mws}	**Mean Wind Speed – Slope** Slope returned from single variant regression with the regression analysis constrained to pass through the origin. A tolerance is imposed on the Slope value. Analysis shall be applied to wind speed ranges a) all above 3 m/s b) 4 to 16 m/s given achieved data coverage requirements.	0.98 – 1.02	0.97 – 1.03
R^2_{mws}	**Mean Wind Speed – Coefficient of Determination** Correlation Co-efficient returned from single variant regression A threshold is imposed on the Correlation Co-efficient value. Analysis shall be applied to wind speed ranges a) all above 3 m/s b) 4 to 16 m/s given achieved data coverage requirements.	>0.98	>0.97

KPI	Definition / Rationale	Acceptance Criteria [1]	
		Best Practice	**Minimum**
X_{mwd}	**Mean Wind Direction – Slope** Slope returned from a two-variant regression. A tolerance is imposed on the Slope value. Analysis shall be applied to a) all wind speeds above 3 m/s regardless of coverage requirements.	0.98– 1.02	0.97 – 1.03
OFF_{mwd}	**Mean Wind Direction – Offset (absolute value)** (same as for M_{mwd})	< 5°	< 7.5°
R^2_{mwd}	**Mean Wind Direction – Coefficient of Determination** (same as for M_{mwd})	> 0.97	> 0.95

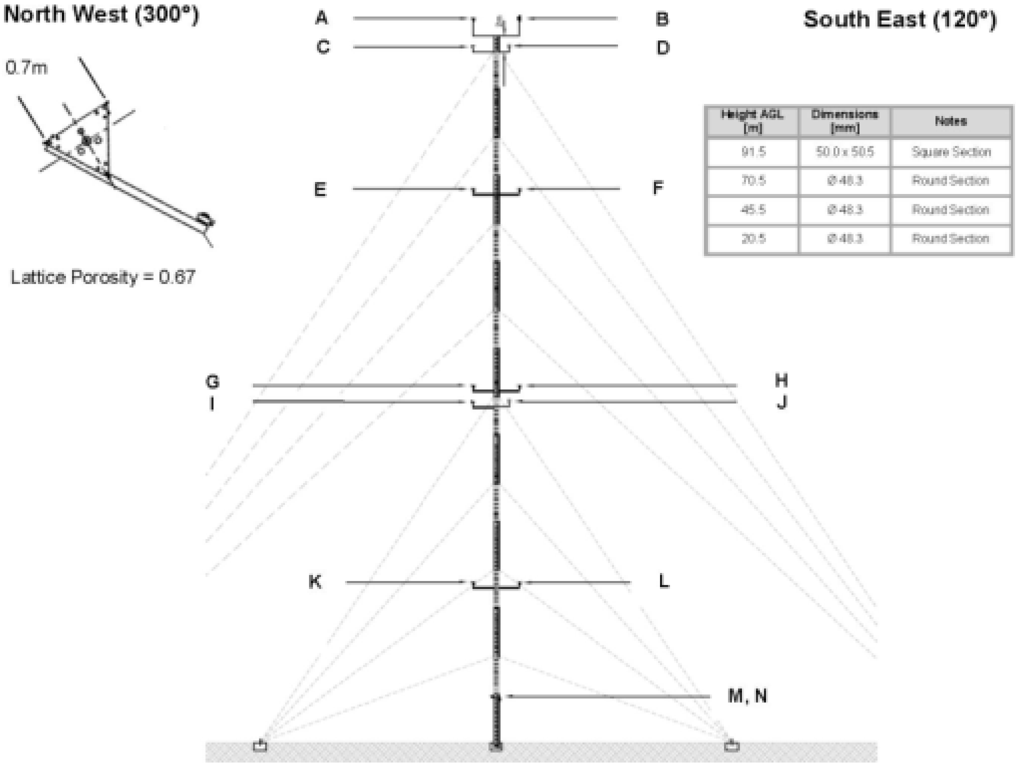
1 Acceptance Criteria in the form of "**best practice**" and "**minimum**" allowable tolerances have been imposed on mean differences, slope and offset values as well as on coefficient of determination returned from each reference height for KPIs related to the primary parameters of interest; wind speed and wind direction. KPIs outside the best practise or minimum acceptance criteria are marked as "**deviation**"

APPENDIX B UK REMOTE SENSING TEST SITE NEAR PERSHORE/THROCKMORTON MET MAST DETAILS

360° Panorama Photos, taken on 2018-04-18, see inspection report [6]:

Met Mast Photo:

Met. Mast Sketch:



Met. Mast Sensor Distribution Table 1:

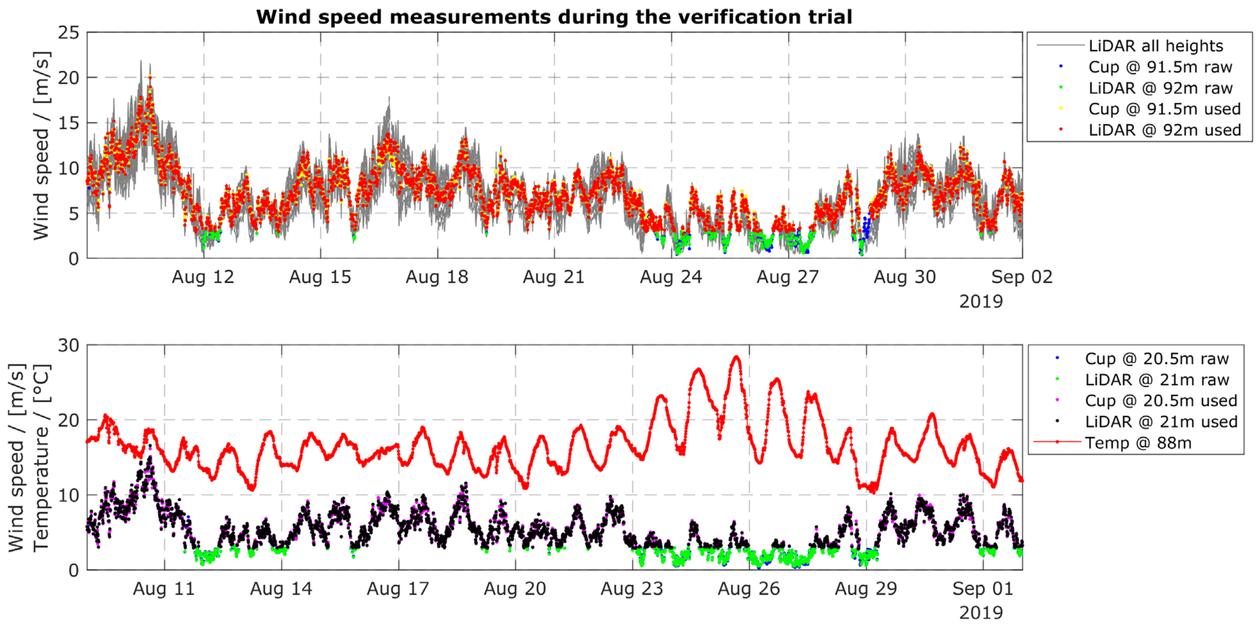
Label	Height [m]	Orientation - Mast to Instrument [°]	Instrument Type	Instrument Model	Cup to Boom Centre Height [mm]	Instrument to Mast Centre Length [mm]
A	91.5	300	Cup Anemometer	Thies First Class Advanced	1520	1025
B	91.5	120	Cup Anemometer	Thies First Class Advanced	1500	1025
C	88	300	3D Sonic Anemometer	Thies Clima 3D Sonic Anemometer	920	3700
D	88	120	Temperature/Humidity	Campbell Scientific CS215	-	-
E	70.5	300	Cup Anemometer	Thies First Class Advanced	960	3700
F	70.5	120	Cup Anemometer	Thies First Class Advanced	915	3700
G	45.5	300	Cup Anemometer	Thies First Class Advanced	955	3700
H	45.5	120	Cup Anemometer	Thies First Class Advanced	1160	3700
I	43.5	300	Direction Vane	Vector W200P	920	3700
J	43.5	120	Temperature/Humidity	Campbell Scientific CS215	-	-
K	20.5	300	Cup Anemometer	Thies First Class Advanced	960	3700
L	20.5	120	Cup Anemometer	Thies First Class Advanced	930	3700
M	-	-	Pressure	Campbell Scientific CS100	-	-
N	-	-	Data Logger	Campbell Scientific CR 1000	-	-

Met. Mast Sensor Distribution Table 2:

Label		A	B	E	F	G	H	K	L
Channel		WS_2R	WS_1M	WS_4R	WS_3V	WS_6R	WS_5V	WS_8R	WS_7V
Model		Thies First Class Advanced	Thies First Class Advanced	Thies First Class Advanced	Thies First Class Advanced	Thies First Class Advanced	Thies First Class Advanced	Thies First Class Advanced	Thies First Class Advanced
S/N		11183812	10164580	11183813	7162397	7162398	11183815	11183814	7162399
Height [m]		91.5	91.5	70.5	70.5	45.5	45.5	20.5	20.5
Orientation - Mast to Instruments [°]		300	120	300	120	300	120	300	120
DWG	Calibration date	20-11-18	22-11-16	20-11-18	10-10-17	10-10-17	20-11-18	20-11-18	10-10-17
	Slope	0.04602	0.04589	0.04606	0.04612	0.04609	0.04594	0.04602	0.04609
	Offset	0.2282	0.2519	0.2256	0.2278	0.2392	0.2362	0.2233	0.2273
Applied		0.04602	0.04589	0.04606	0.04612	0.04609	0.04594	0.04602	0.04609
		0.2282	0.2519	0.2256	0.2278	0.2392	0.2362	0.2233	0.2273

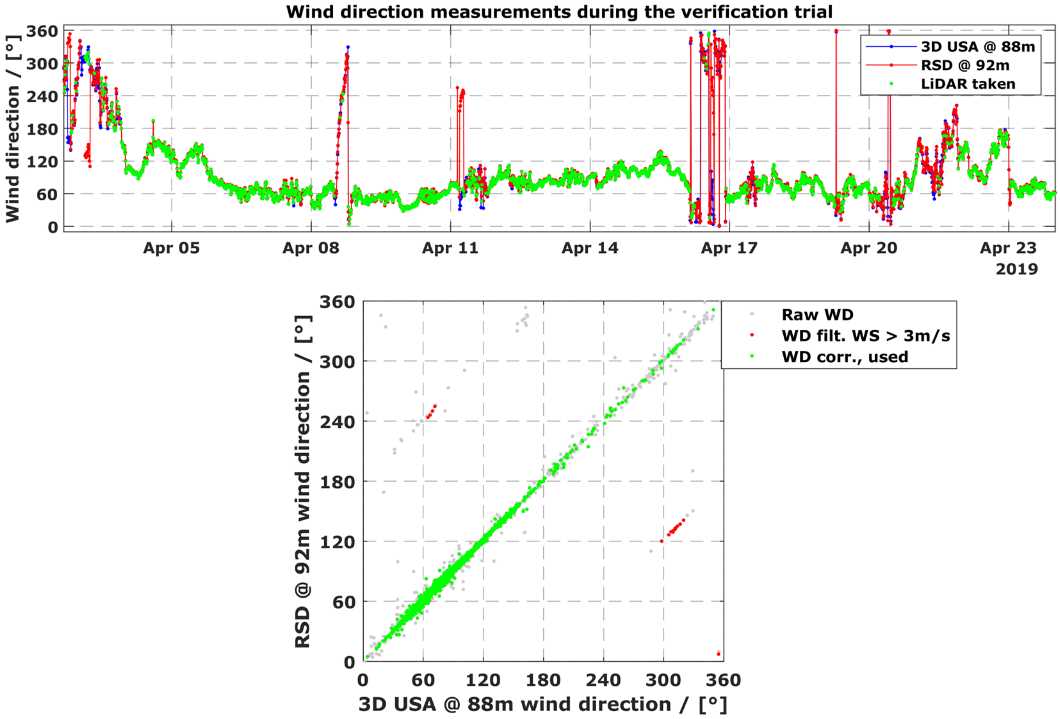
APPENDIX C TIME SERIES OF WIND SPEED

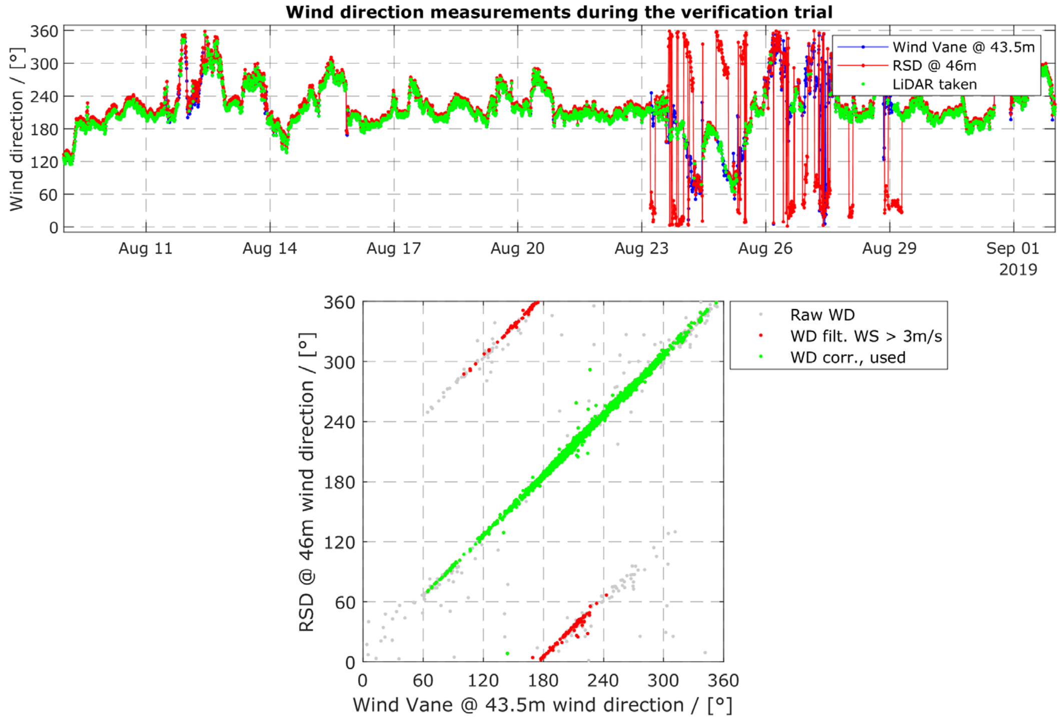
Wind Speed time series for 92 m (upper panel) and 21 m (lower panel). The bottom plot includes temperature time series (red) from mast sensor.



APPENDIX D WIND DIRECTION

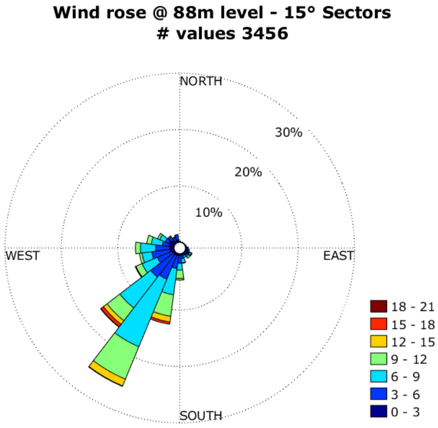
WD time series at 88 m and 43.5 m sonic/vane levels:

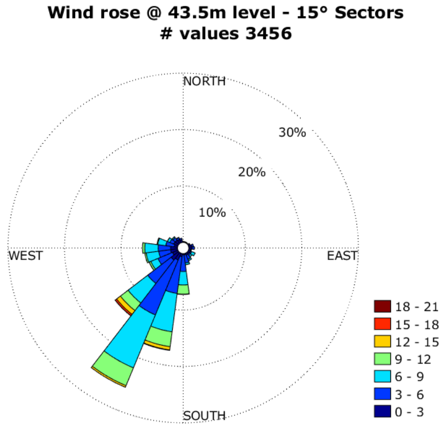




X-Y-plot of wind direction data for WS > 3 m/s (red dots) and 180° ambiguity corrected data (green dots) between sonic/wind vane and Lidar measures

Wind rose and sector averaged WS distribution for 88/90m and 43.5/46m:





APPENDIX E CUP CALIBRATION CERTIFICATES

TFCA Cup S/N 11183812 at 91.5 m, 300° orientation (Deutsche WindGuard Calibration)

A

DEUTSCHE WINDGUARD

Deutsche WindGuard
Wind Tunnel Services GmbH

IECRE and MEASNET approved test laboratory

accredited by the / *akkreditiert durch die*

Deutsche Akkreditierungsstelle GmbH

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

DAkkS Deutsche Akkreditierungsstelle D-K-15140-01-00

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

1814599
D-K-15140-01-00
11/2018

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.10.000
Serial number *Fabrikat/Serien-Nr.*	11183812
Customer *Auftraggeber*	Thies Clima D-37083 Göttingen
Order No. *Auftragsnummer*	AB1805525
Project No. *Projektnummer*	VT181098
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	20.11.2018

This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
The DAkkS is signatory to the multilateral agreements of the European co-operation for Accreditation (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.
The user is obliged to have the object recalibrated at appropriate intervals.
Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).
Die DAkkS ist Unterzeichner der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine.
Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
20.11.2018	D. Westermann Dipl. Phys. Dieter Westermann	B. Schütz Techniker Bendix Schütz

Page 2 / 4
Seite

1814599
D-K-15140-01-00
11/2018

Calibration object *Kalibriergegenstand*	Cup Anemometer	
Calibration procedure *Kalibrierverfahren*	IEC 61400-12-1:2017	
Place of calibration *Ort der Kalibrierung*	Wind tunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel	
Test conditions *Messbedingungen*	wind tunnel area	10000 cm²
	anemometer frontal area	230 cm²
	diameter of mounting pipe	33.7 mm EN 10217
	blockage ratio [1)]	0.023 [-]
	software version	P_7.8.07

[1)] Due to the special construction of the test section no blockage correction is necessary.

Ambient conditions *Umgebungsbedingungen*	air temperature	20.0 °C ± 0.1 °C
	air pressure	1013.8 hPa ± 0.3 hPa
	relative air humidity	37.9 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k=2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.
The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische Bundesanstalt) standard for flow speed. It is realized by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2 %, k=2)

Additional remarks
Zusätzliche Anmerkungen

-

Page 3 / 4
Seite

1814599
D-K-15140-01-00
11/2018

Calibration result
Kalibrierergebnis

Reference Air velocity m/s	Reference Unc m/s	Test item Output Hz
3.942	0.05	80.940
5.845	0.05	122.190
7.820	0.05	165.077
9.813	0.05	208.550
11.807	0.05	251.032
13.717	0.05	292.881
15.665	0.05	335.958
14.672	0.05	313.698
12.795	0.05	272.862
10.774	0.05	229.502
8.815	0.05	186.399
6.878	0.05	144.086
4.896	0.05	101.333

Statistical analysis

Slope	0.04602 (m/s)/(Hz) ±0.00005 (m/s)/(Hz)
Offset	0.2282 m/s ±0.012 m/s
Standard error (Y)	0.012 m/s
Correlation coefficient	0.999993

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel Services GmbH - measnet

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

1814599
D-K-15140-01-00
11/2018

Graphical representation of the result
Grafische Darstellung des Ergebnisses

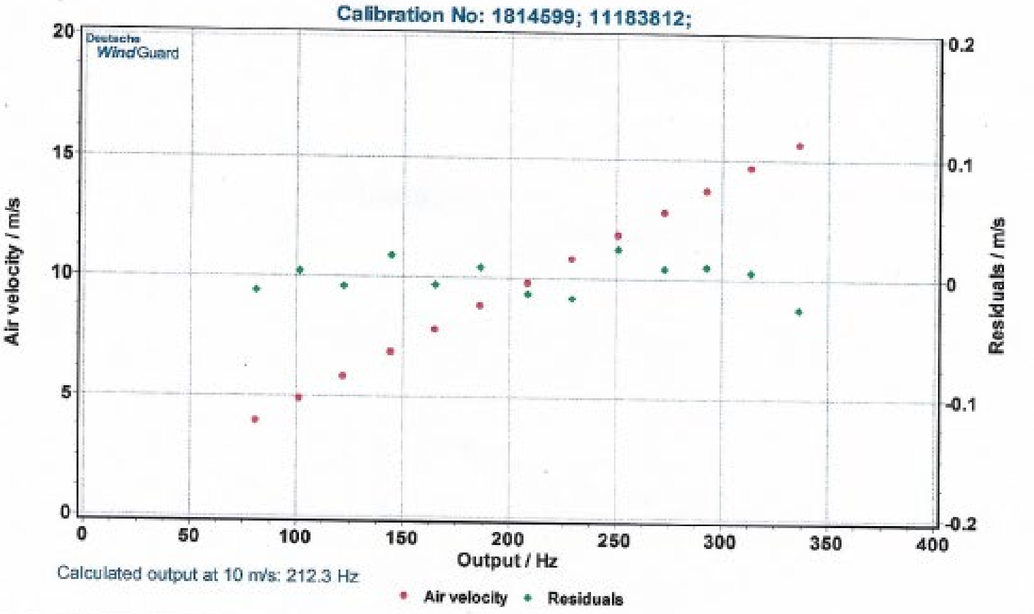


Photo of the measurement setup
Foto des Messaufbaus

Remark: The proportions of the set-up may not be true to scale due to imaging geometry.

TFCA Cup S/N 10164580 at 91.5 m, 120° orientation (Deutsche WindGuard Calibration)

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

accredited by the / *akkreditiert durch die*

Deutsche Akkreditierungsstelle GmbH

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

ilac-MRA DAkkS Deutsche Akkreditierungsstelle D-K-15140-01-00

Calibration certificate *Kalibrierschein*	Calibration mark *Kalibrierzeichen*	1615854 D-K- 15140-01-00 11/2016

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.10.000
Serial number *Fabrikat/Serien-Nr.*	10164580
Customer *Auftraggeber*	Ammonit Measurement GmbH D-10997 Berlin
Order No. *Auftragsnummer*	L24199
Project No. *Projektnummer*	VT161016
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	22.11.2016

This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
The DAkkS is signatory to the multilateral agreements of the European co-operation for Accreditation (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.
The user is obliged to have the object recalibrated at appropriate intervals.
Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).
Die DAkkS ist Unterzeichner der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine.
Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
22.11.2016	D. Westermann Dipl. Phys. Dieter Westermann	D. Henninges Techniker Dirk Henninges

1615854
D-K- 15140-01-00
11/2016

Calibration object
Kalibriergegenstand

Cup Anemometer

Calibration procedure
Kalibrierverfahren

• Deutsche WindGuard Wind Tunnel Services: QM-KL-AK-VA
Based on following standards:
• MEASNET: Anemometer calibration procedure
• IEC 61400-12-1: Power performance measurements of electricity producing wind turbines
• IEC 61400-12-2: Power performance of electricity producing wind turbines based on nacelle anemometry
• ISO 3966: Measurement of fluid in closed conduits
• ISO 16622: Meteorology - Sonic anemometers/thermometers

Place of calibration
Ort der Kalibrierung

Windtunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions
Messbedingungen

wind tunnel area	10000 cm²
anemometer frontal area	230 cm²
diameter of mounting pipe	34 mm
blockage ratio [1)]	0.023 [-]
software version	7.64

[1)] Due to the special construction of the test section no blockage correction is necessary.

Ambient conditions
Umgebungsbedingungen

air temperature	20.5 °C ± 0.1 °C
air pressure	1008.7 hPa ± 0.3 hPa
relative air humidity	43.1 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k = 2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.
The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische Bundesanstalt) standard for flow speed. It is realized by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2 %, k=2)

Additional remarks
Zusätzliche Anmerkungen

-

Page 3 / 4
Seite

1615854
D-K-15140-01-00
11/2016

Calibration result
Kalibrierergebnis

Sensor out Hz	Tunnel speed m/s	Uncertainty (k=2) m/s
81.749	4.003	0.050
123.380	5.924	0.050
167.453	7.938	0.051
211.193	9.962	0.051
255.657	11.989	0.052
297.259	13.906	0.053
340.409	15.894	0.053
318.978	14.893	0.053
277.463	12.985	0.053
232.804	10.958	0.051
188.551	8.927	0.051
145.825	6.988	0.051
102.503	4.962	0.050

File: 1615854

Statistical analysis

Slope	0.04589 (m/s)/(Hz) ±0.00005 (m/s)/(Hz)
Offset	0.2653 m/s ±0.010 m/s
Standard error (Y)	0.010 m/s
Correlation coefficient	0.999995

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel Services GmbH measnet

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

Page 4 / 4
Seite

1615854
D-K-15140-01-00
11/2016

Graphical representation of the result
Grafische Darstellung des Ergebnisses

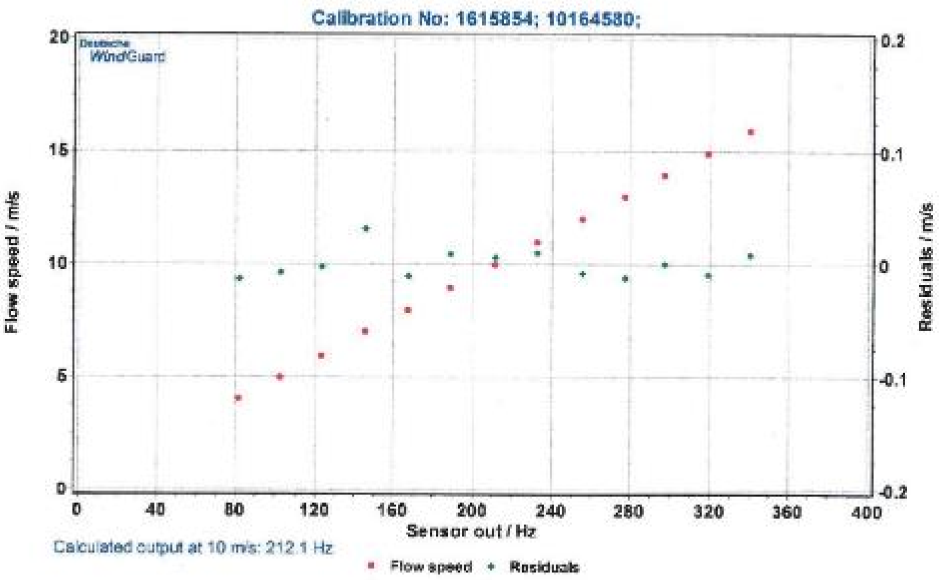


Photo of the measurement setup
Foto des Messaufbaus

Remark: The proportions of the set-up may not be true to scale due to imaging geometry.

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

TFCA Cup S/N 11183813 at 70.5 m, 300° orientation (Deutsche WindGuard Calibration)

E

DEUTSCHE WINDGUARD

Deutsche WindGuard
Wind Tunnel Services GmbH

IECRE and MEASNET approved test laboratory

accredited by the / *akkreditiert durch die*

Deutsche Akkreditierungsstelle GmbH

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

DAkkS Deutsche Akkreditierungsstelle D-K-15140-01-00

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

1814600
D-K-15140-01-00
11/2018

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.10.000
Serial number *Fabrikat/Serien-Nr.*	11183813
Customer *Auftraggeber*	Thies Clima D-37083 Göttingen
Order No. *Auftragsnummer*	AB1805525
Project No. *Projektnummer*	VT181098
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	20.11.2018

This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
The DAkkS is signatory to the multilateral agreements of the European co-operation for Accreditation (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.
The user is obliged to have the object recalibrated at appropriate intervals.
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Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
20.11.2018	D. Westermann Dipl. Phys. Dieter Westermann	B. Schütz Techniker Bendix Schütz

1814600
D-K- 15140-01-00
11/2018

Calibration object *Kalibriergegenstand*	Cup Anemometer	
Calibration procedure *Kalibrierverfahren*	IEC 61400-12-1:2017	
Place of calibration *Ort der Kalibrierung*	Wind tunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel	
Test conditions *Messbedingungen*	wind tunnel area	10000 cm²
	anemometer frontal area	230 cm²
	diameter of mounting pipe	33.7 mm EN 10217
	blockage ratio [1)]	0.023 [-]
	software version	P_7.8.07

[1)] Due to the special construction of the test section no blockage correction is necessary.

Ambient conditions *Umgebungsbedingungen*	air temperature	20.0 °C ± 0.1 °C
	air pressure	1013.7 hPa ± 0.3 hPa
	relative air humidity	37.9 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k=2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.
The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische Bundesanstalt) standard for flow speed. It is realized by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2 %, k=2)

Additional remarks
Zusätzliche Anmerkungen

-

1814600
D-K-15140-01-00
11/2018

Calibration result
Kalibrierergebnis

Reference Air velocity m/s	Reference Unc m/s	Test item Output Hz
3.939	0.05	80.785
5.837	0.05	122.112
7.814	0.05	164.957
9.817	0.05	208.844
11.802	0.05	250.844
13.711	0.05	292.371
15.666	0.05	335.260
14.676	0.05	314.059
12.791	0.05	273.063
10.787	0.05	229.137
8.796	0.05	186.044
6.876	0.05	144.048
4.904	0.05	101.250

Statistical analysis

Slope	0.04606 (m/s)/(Hz) ±0.00006 (m/s)/(Hz)
Offset	0.2256 m/s ±0.012 m/s
Standard error (Y)	0.013 m/s
Correlation coefficient	0.999992

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel Services GmbH · measnet

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

1814600
D-K-15140-01-00
11/2018

Graphical representation of the result
Grafische Darstellung des Ergebnisses

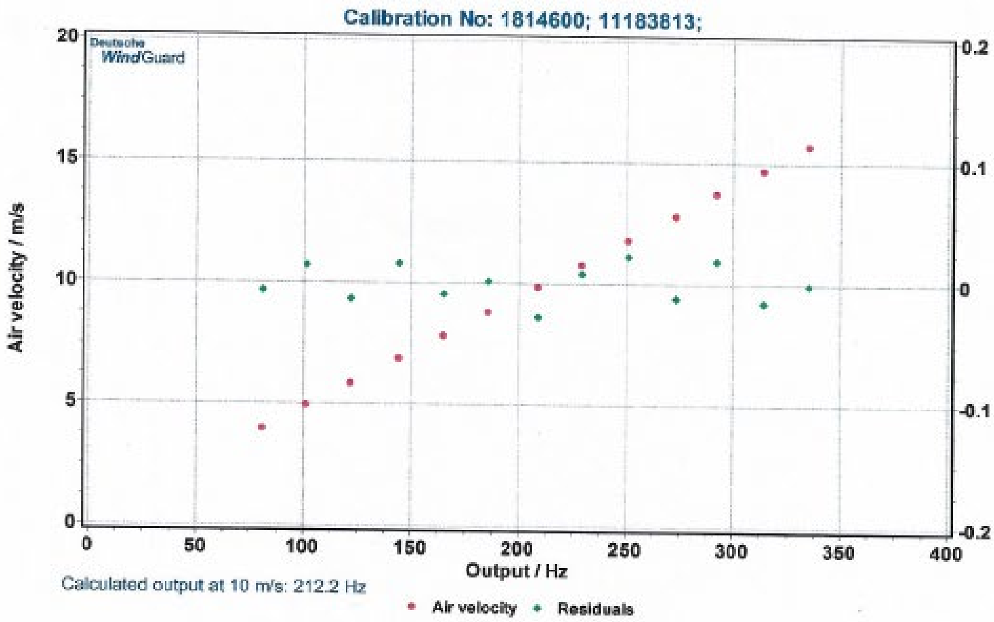
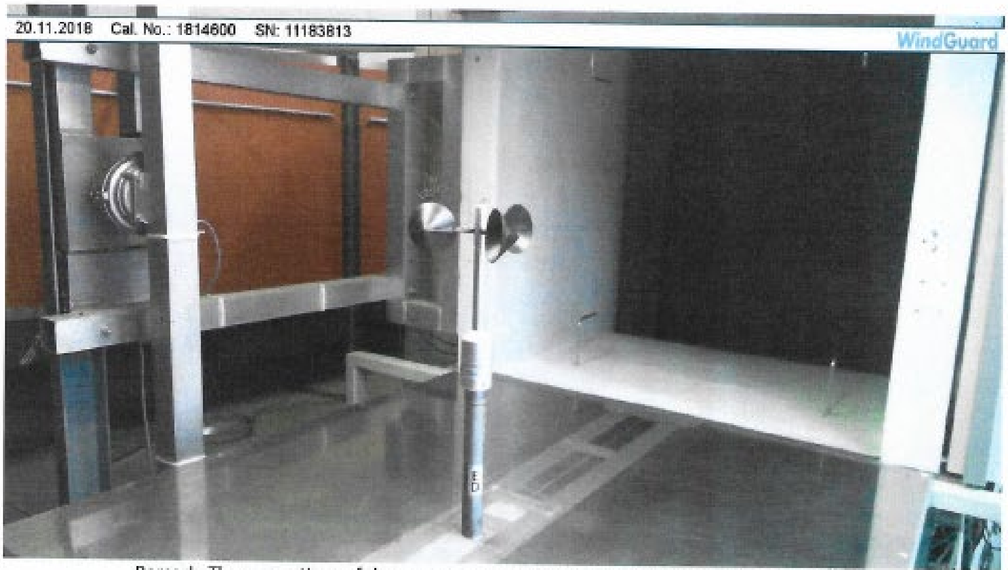


Photo of the measurement setup
Foto des Messaufbaus



Remark: The proportions of the set-up may not be true to scale due to imaging geometry.

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

TFCA Cup S/N 07162397 at 70.5 m, 120° orientation (Deutsche WindGuard Calibration)

ZEPHIR : THROCKMORTON REFIT 4 STAGE 1

MAST POSITION: F _ 70·5

DEUTSCHE WINDGUARD

Deutsche WindGuard Wind Tunnel Services GmbH

IECRE and MEASNET approved test laboratory

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Deutsche Akkreditierungsstelle GmbH

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

DAkkS Deutsche Akkreditierungsstelle D-K-15140-01-00

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

1714175
D-K-15140-01-00
10/2017

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.10.000
Serial number *Fabrikat/Serien-Nr.*	07162397
Customer *Auftraggeber*	Dulas Ltd UK SY20 8AX Machynlleth
Order No. *Auftragsnummer*	25478
Project No. *Projektnummer*	VT170988
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	10.10.2017

This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
The DAkkS is signatory to the multilateral agreements of the European co-operation for Accreditation (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.
The user is obliged to have the object recalibrated at appropriate intervals.

Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).
Die DAkkS ist Unterzeichner der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine.
Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

This calibration certificate may not be reproduced other than in full except with the permission of both the German Accreditation Body and the issuing laboratory. Calibration certificates without signature are not valid. This calibration certificate has been generated electronically.
Dieser Kalibrierschein darf nur vollständig und unverändert weiterverbreitet werden. Auszüge oder Änderungen bedürfen der Genehmigung sowohl der Deutschen Akkreditierungsstelle als auch des ausstellenden Kalibrierlaboratoriums. Kalibrierscheine ohne Unterschrift haben keine Gültigkeit. Dieser Kalibrierschein wurde elektronisch erzeugt.

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
10.10.2017	D. Westermann Dipl. Phys. Dieter Westermann	D. Henninges Techniker Dirk Henninges

1714175
D-K- 15140-01-00
10/2017

Calibration object
Kalibriergegenstand

Cup Anemometer

Calibration procedure
Kalibrierverfahren

• Deutsche WindGuard Wind Tunnel Services: QM-KL-AK-VA
Based on following standards:
• MEASNET: Anemometer calibration procedure
• IEC 61400-12-1: Power performance measurements of electricity producing wind turbines
• IEC 61400-12-2: Power performance of electricity producing wind turbines based on nacelle anemometry
• ISO 3966: Measurement of fluid in closed conduits
• ISO 16622: Meteorology - Sonic anemometers/thermometers

Place of calibration
Ort der Kalibrierung

Windtunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions
Messbedingungen

wind tunnel area	10000 cm^2
anemometer frontal area	230 cm^2
diameter of mounting pipe	34 mm
blockage ratio [1)]	0.023 [-]
software version	7.7

[1)] Due to the special construction of the test section no blockage correction is necessary.

Ambient conditions
Umgebungsbedingungen

air temperature	23.9 °C ± 0.1 °C
air pressure	1011.4 hPa ± 0.3 hPa
relative air humidity	46.9 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k=2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.
The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische Bundesanstalt) standard for flow speed. It is realized by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2 %, k=2)

Additional remarks
Zusätzliche Anmerkungen

-

1714175
D-K-15140-01-00
10/2017

Calibration result
Kalibrierergebnis

Sensor Hz	Tunnel Speed m/s	Uncertainty m/s
81.768	3.975	0.050
122.798	5.879	0.050
166.419	7.889	0.051
210.089	9.915	0.051
253.221	11.936	0.051
295.387	13.866	0.052
339.010	15.832	0.052
316.658	14.833	0.053
275.538	12.925	0.052
230.633	10.863	0.051
186.934	8.881	0.051
145.013	6.934	0.051
102.057	4.940	0.050

File: 1714175

Statistical analysis

Slope	0.04612 (m/s)/(Hz) ±0.00007 (m/s)/(Hz)
Offset	0.2278 m/s ±0.016 m/s
Standard error (Y)	0.016 m/s
Correlation coefficient	0.999988

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Graphical representation of the result
Grafische Darstellung des Ergebnisses

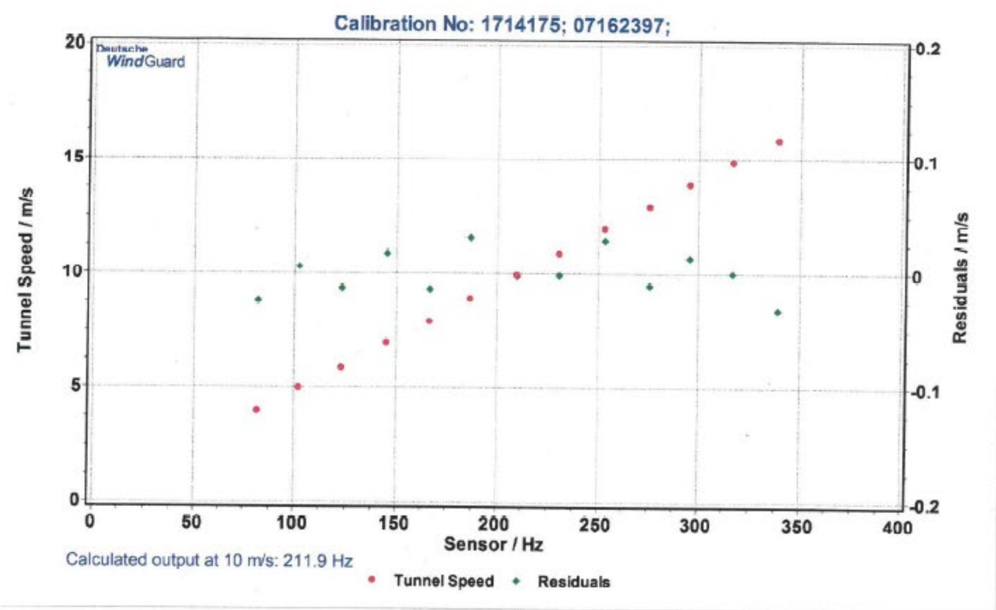
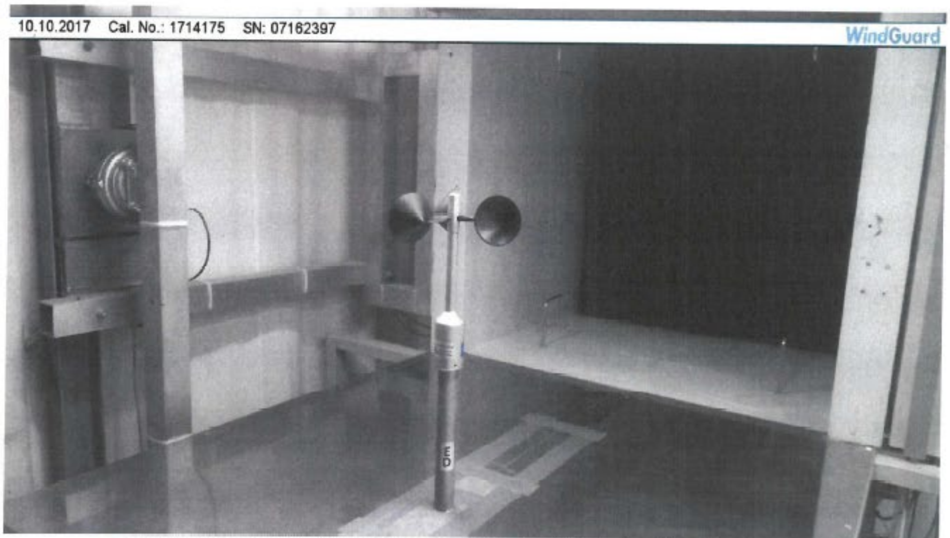


Photo of the measurement setup
Foto des Messaufbaus



Remark: The proportions of the set-up may not be true to scale due to imaging geometry.

TFCA Cup S/N 07162398 at 45.5 m, 300° orientation (Deutsche WindGuard Calibration)

: THROCKMORTON REFIT 4 STAGE 2

POSITION: G_45.5

DEUTSCHE WINDGUARD

Deutsche WindGuard
Wind Tunnel Services GmbH

IECRE and MEASNET approved test laboratory

accredited by the / *akkreditiert durch die*

Deutsche Akkreditierungsstelle GmbH

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

DAkkS Deutsche Akkreditierungsstelle D-K-15140-01-00

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

1714176
D-K-15140-01-00
10/2017

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.10.000
Serial number *Fabrikat/Serien-Nr.*	07162398
Customer *Auftraggeber*	Dulas Ltd UK SY20 8AX Machynlleth
Order No. *Auftragsnummer*	25478
Project No. *Projektnummer*	VT170988
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	10.10.2017

This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
The DAkkS is signatory to the multilateral agreements of the European co-operation for Accreditation (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.
The user is obliged to have the object recalibrated at appropriate intervals.

Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).
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Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
10.10.2017	D. Westermann Dipl. Phys. Dieter Westermann	D. Henninges Techniker Dirk Henninges

1714176
D-K-15140-01-00
10/2017

Calibration object
Kalibriergegenstand

Cup Anemometer

Calibration procedure
Kalibrierverfahren

- Deutsche WindGuard Wind Tunnel Services: QM-KL-AK-VA

Based on following standards:

- MEASNET: Anemometer calibration procedure
- IEC 61400-12-1: Power performance measurements of electricity producing wind turbines
- IEC 61400-12-2: Power performance of electricity producing wind turbines based on nacelle anemometry
- ISO 3966: Measurement of fluid in closed conduits
- ISO 16622: Meteorology - Sonic anemometers/thermometers

Place of calibration
Ort der Kalibrierung

Windtunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions
Messbedingungen

wind tunnel area	10000 cm²
anemometer frontal area	230 cm²
diameter of mounting pipe	34 mm
blockage ratio [1)]	0.023 [-]
software version	7.7

[1)] Due to the special construction of the test section no blockage correction is necessary.

Ambient conditions
Umgebungsbedingungen

air temperature	24.0 °C ± 0.1 °C
air pressure	1011.4 hPa ± 0.3 hPa
relative air humidity	46.8 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k=2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.
The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische Bundesanstalt) standard for flow speed. It is realized by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2 %, k=2)

Additional remarks
Zusätzliche Anmerkungen

-

1714176
D-K-15140-01-00
10/2017

Calibration result
Kalibrierergebnis

Sensor Hz	Tunnel Speed m/s	Uncertainty m/s
81.445	3.971	0.050
122.962	5.898	0.051
166.326	7.901	0.051
209.879	9.910	0.051
253.444	11.927	0.051
295.193	13.847	0.052
338.868	15.829	0.053
316.031	14.830	0.052
275.890	12.922	0.051
230.588	10.887	0.051
187.056	8.877	0.051
145.025	6.933	0.050
101.747	4.936	0.050

File: 1714176

Statistical analysis

Slope	0.04609 (m/s)/(Hz) ±0.00007 (m/s)/(Hz)
Offset	0.2392 m/s ±0.015 m/s
Standard error (Y)	0.015 m/s
Correlation coefficient	0.999989

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel Services GmbH measnet

1714176
D-K-15140-01-00
10/2017

Graphical representation of the result
Grafische Darstellung des Ergebnisses

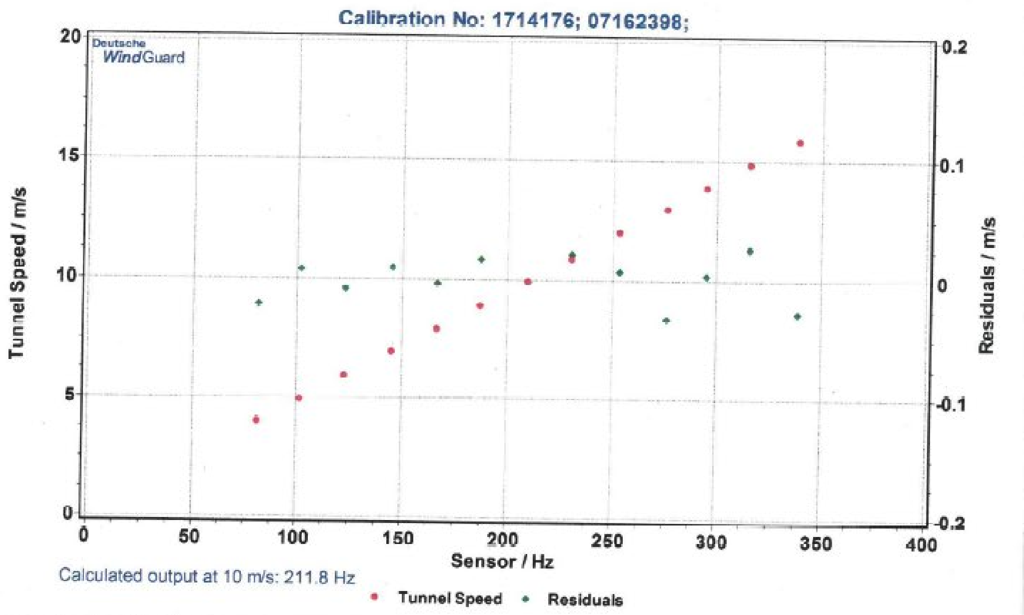
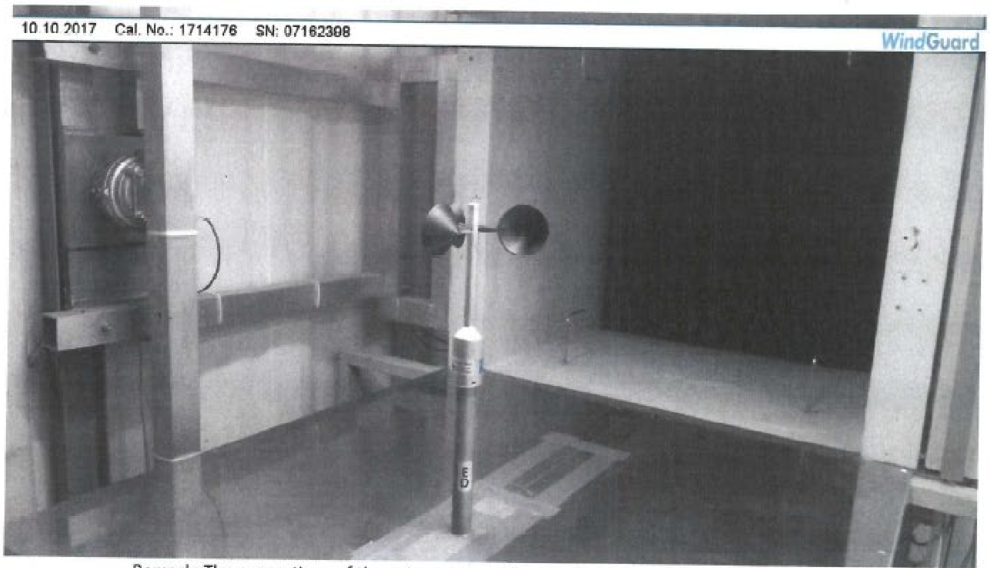


Photo of the measurement setup
Foto des Messaufbaus



Remark: The proportions of the set-up may not be true to scale due to imaging geometry.

TFCA Cup S/N 11183815 at 45.5 m, 120° orientation (Deutsche WindGuard Calibration)

H

DEUTSCHE WINDGUARD

Deutsche WindGuard Wind Tunnel Services GmbH

IECRE and MEASNET approved test laboratory

accredited by the / *akkreditiert durch die*

Deutsche Akkreditierungsstelle GmbH

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

DAkkS Deutsche Akkreditierungsstelle D-K-15140-01-00

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

1814602
D-K-15140-01-00
11/2018

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.10.000
Serial number *Fabrikat/Serien-Nr.*	11183815
Customer *Auftraggeber*	Thies Clima D-37083 Göttingen
Order No. *Auftragsnummer*	AB1805525
Project No. *Projektnummer*	VT181098
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	20.11.2018

This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
The DAkkS is signatory to the multilateral agreements of the European co-operation for Accreditation (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.
The user is obliged to have the object recalibrated at appropriate intervals.
Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).
Die DAkkS ist Unterzeichner der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine.
Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

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Dieser Kalibrierschein darf nur vollständig und unverändert weiterverbreitet werden. Auszüge oder Änderungen bedürfen der Genehmigung sowohl der Deutschen Akkreditierungsstelle als auch des ausstellenden Kalibrierlaboratoriums. Kalibrierscheine ohne Unterschrift haben keine Gültigkeit. Dieser Kalibrierschein wurde elektronisch erzeugt.

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
20.11.2018	D. Westermann Dipl. Phys. Dieter Westermann	B. Schütz Techniker Bendix Schütz

Page 2 / 4
Seite

1814602
D-K-15140-01-00
11/2018

Calibration object *Kalibriergegenstand*	Cup Anemometer	
Calibration procedure *Kalibrierverfahren*	IEC 61400-12-1:2017	
Place of calibration *Ort der Kalibrierung*	Wind tunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel	
Test conditions *Messbedingungen*	wind tunnel area	10000 cm²
	anemometer frontal area	230 cm²
	diameter of mounting pipe	33.7 mm EN 10217
	blockage ratio [1)]	0.023 [-]
	software version	P_7.8.07

[1)] Due to the special construction of the test section no blockage correction is necessary.

Ambient conditions *Umgebungsbedingungen*	air temperature	20.1 °C ± 0.1 °C
	air pressure	1013.8 hPa ± 0.3 hPa
	relative air humidity	37.8 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k=2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.
The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische Bundesanstalt) standard for flow speed. It is realized by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2 %, k=2)

Additional remarks
Zusätzliche Anmerkungen

-

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

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1814602
D-K- 15140-01-00
11/2018

Calibration result
Kalibrierergebnis

Reference Air velocity m/s	Reference Unc m/s	Test item Output Hz
3.937	0.05	80.406
5.857	0.05	122.569
7.827	0.05	165.645
9.824	0.05	208.623
11.807	0.05	252.055
13.722	0.05	293.683
15.666	0.05	335.973
14.679	0.05	314.451
12.779	0.05	273.019
10.774	0.05	228.625
8.794	0.05	185.753
6.888	0.05	145.007
4.903	0.05	101.648

Statistical analysis		
	Slope	0.04594 (m/s)/(Hz) ±0.00005 (m/s)/(Hz)
	Offset	0.2362 m/s ±0.012 m/s
	Standard error (Y)	0.012 m/s
	Correlation coefficient	0.999993

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel Services GmbH

Page 4 / 4
Seite

1814602
D-K-15140-01-00
11/2018

Graphical representation of the result
Grafische Darstellung des Ergebnisses

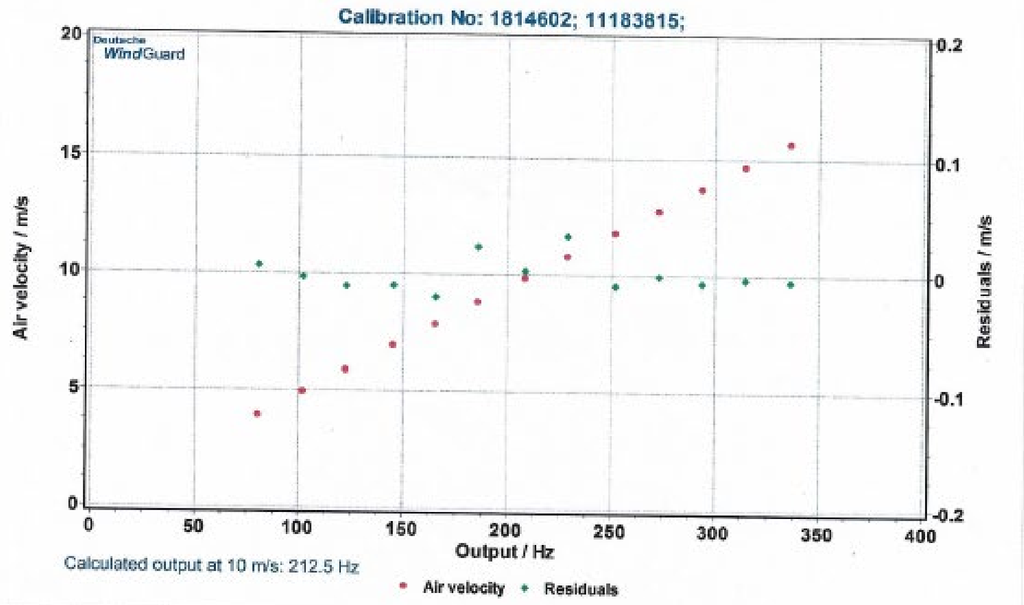

Photo of the measurement setup
Foto des Messaufbaus

Remark: The proportions of the set-up may not be true to scale due to imaging geometry.

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

TFCA Cup S/N 11183814 at 20.5 m, 300° orientation (Deutsche WindGuard Calibration)

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Deutsche WindGuard Wind Tunnel Services GmbH

IECRE and MEASNET approved test laboratory

accredited by the / *akkreditiert durch die*

Deutsche Akkreditierungsstelle GmbH

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

DAkkS Deutsche Akkreditierungsstelle D-K-15140-01-00

1814601
D-K-15140-01-00
11/2018

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.10.000
Serial number *Fabrikat/Serien-Nr.*	11183814
Customer *Auftraggeber*	Thies Clima D-37083 Göttingen
Order No. *Auftragsnummer*	AB1805525
Project No. *Projektnummer*	VT181098
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	20.11.2018

This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
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Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
20.11.2018	D. Westermann Dipl. Phys. Dieter Westermann	B. Schütz Techniker Bendix Schütz

1814601
D-K- 15140-01-00
11/2018

Calibration object *Kalibriergegenstand*	Cup Anemometer	
Calibration procedure *Kalibrierverfahren*	IEC 61400-12-1:2017	
Place of calibration *Ort der Kalibrierung*	Wind tunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel	
Test conditions *Messbedingungen*	wind tunnel area	10000 cm²
	anemometer frontal area	230 cm²
	diameter of mounting pipe	33.7 mm EN 10217
	blockage ratio [1)]	0.023 [-]
	software version	P_7.8.07

[1)] Due to the special construction of the test section no blockage correction is necessary.

Ambient conditions *Umgebungsbedingungen*	air temperature	20.1 °C ± 0.1 °C
	air pressure	1013.8 hPa ± 0.3 hPa
	relative air humidity	37.8 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k=2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.
The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische Bundesanstalt) standard for flow speed. It is realized by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2 %, k=2)

Additional remarks
Zusätzliche Anmerkungen

-

1814601
D-K-
15140-01-00
11/2018

Calibration result
Kalibrierergebnis

Reference Air velocity m/s	Reference Unc m/s	Test item Output Hz
3.938	0.05	81.174
5.861	0.05	122.972
7.828	0.05	165.731
9.828	0.05	208.668
11.813	0.05	252.338
13.719	0.05	293.054
15.665	0.05	336.267
14.671	0.05	313.675
12.795	0.05	272.981
10.782	0.05	229.057
8.804	0.05	185.725
6.893	0.05	144.442
4.900	0.05	101.365

Statistical analysis

Slope	0.04602 (m/s)/(Hz) ±0.00008 (m/s)/(Hz)
Offset	0.2233 m/s ±0.017 m/s
Standard error (Y)	0.017 m/s
Correlation coefficient	0.999984

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard - Wind Tunnel Services GmbH - measnet

1814601
D-K-15140-01-00
11/2018

Graphical representation of the result
Grafische Darstellung des Ergebnisses

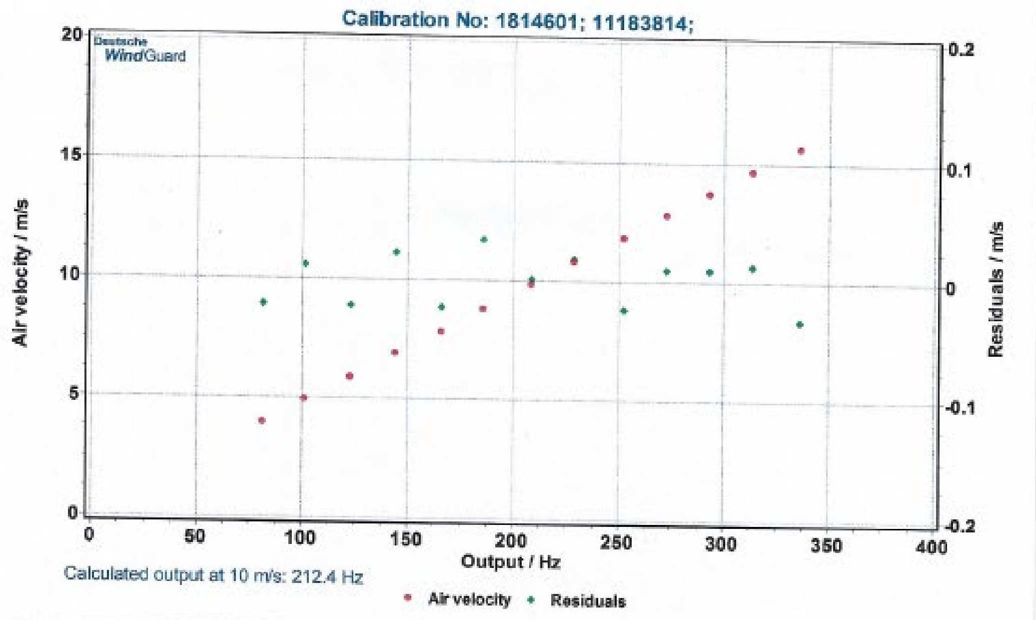

Photo of the measurement setup
Foto des Messaufbaus

Remark: The proportions of the set-up may not be true to scale due to imaging geometry.

TFCA Cup S/N 07162399 at 20.5 m, 120° orientation (Deutsche WindGuard Calibration)

ZEPHIR: THROCKMORTON REFIT 4 STAGE 1
MAST POSITION: L - 20.5

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Deutsche Akkreditierungsstelle GmbH

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

DAkkS Deutsche Akkreditierungsstelle D-K-15140-01-00

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

1714177
D-K-
15140-01-00
10/2017

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D 37083 Göttingen
Type *Typ*	4.3351.10.000
Serial number *Fabrikat/Serien-Nr.*	07162399
Customer *Auftraggeber*	Dulas Ltd UK SY20 8AX Machynlleth
Order No. *Auftragsnummer*	25478
Project No. *Projektnummer*	VT170988
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	10.10.2017

This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
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Die DAkkS ist Unterzeichner der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine.
Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
10.10.2017	Dipl. Phys. Dieter Westermann	Techniker Dirk Henninges

Calibration object
Kalibriergegenstand

Cup Anemometer

Calibration procedure
Kalibrierverfahren

- Deutsche WindGuard Wind Tunnel Services: QM-KL-AK-VA

Based on following standards:

- MEASNET: Anemometer calibration procedure
- IEC 61400-12-1: Power performance measurements of electricity producing wind turbines
- IEC 61400-12-2: Power performance of electricity producing wind turbines based on nacelle anemometry
- ISO 3966: Measurement of fluid in closed conduits
- ISO 16622: Meteorology - Sonic anemometers/thermometers

Place of calibration
Ort der Kalibrierung

Windtunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions
Messbedingungen

wind tunnel area	10000 cm^2
anemometer frontal area	230 cm^2
diameter of mounting pipe	34 mm
blockage ratio [1)]	0.023 [-]
software version	7.7

[1)] Due to the special construction of the test section no blockage correction is necessary.

Ambient conditions
Umgebungsbedingungen

air temperature	24.2 °C ± 0.1 °C
air pressure	1011.3 hPa ± 0.3 hPa
relative air humidity	46.7 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k=2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.
The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische Bundesanstalt) standard for flow speed. It is realized by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2 %, k=2)

Additional remarks
Zusätzliche Anmerkungen

-

1714177
D-K-
15140-01-00
10/2017

Calibration result
Kalibrierergebnis

Sensor Hz	Tunnel Speed m/s	Uncertainty m/s
81.982	3.979	0.050
123.065	5.893	0.050
166.235	7.897	0.051
209.967	9.905	0.051
253.956	11.932	0.051
295.202	13.853	0.052
339.627	15.833	0.053
316.631	14.826	0.052
275.056	12.921	0.052
230.795	10.878	0.052
187.274	8.871	0.051
145.136	6.933	0.051
102.322	4.938	0.050

File: 1714177

Statistical analysis

Slope	0.04609 (m/s)/(Hz) ±0.00007 (m/s)/(Hz)
Offset	0.2273 m/s ±0.016 m/s
Standard error (Y)	0.016 m/s
Correlation coefficient	0.999988

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel Services measnet

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

1714177
D-K- 15140-01-00
10/2017

Graphical representation of the result
Grafische Darstellung des Ergebnisses

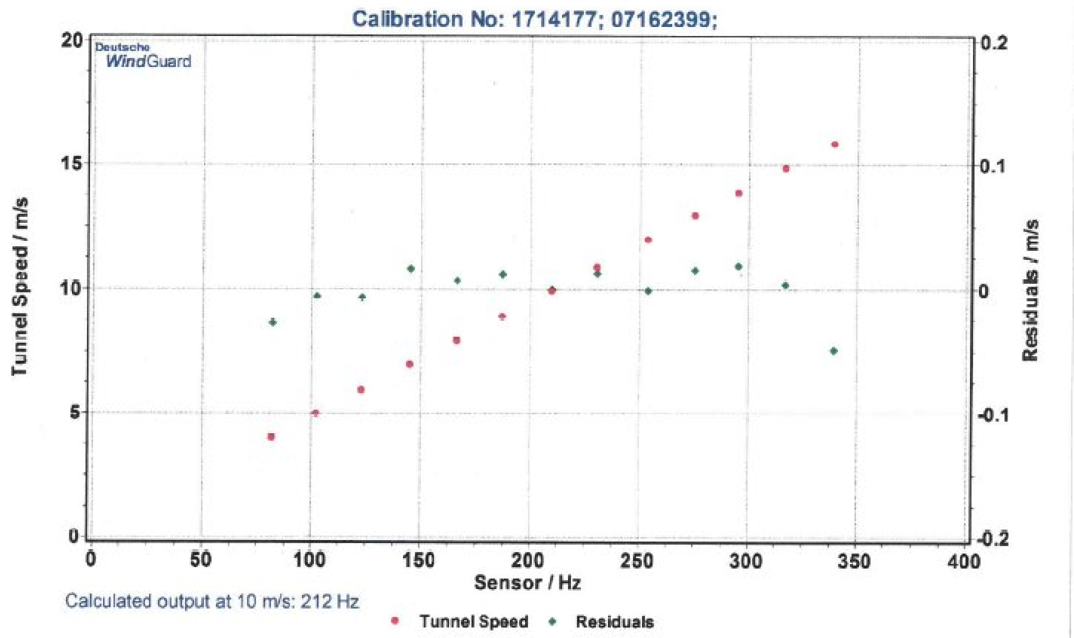
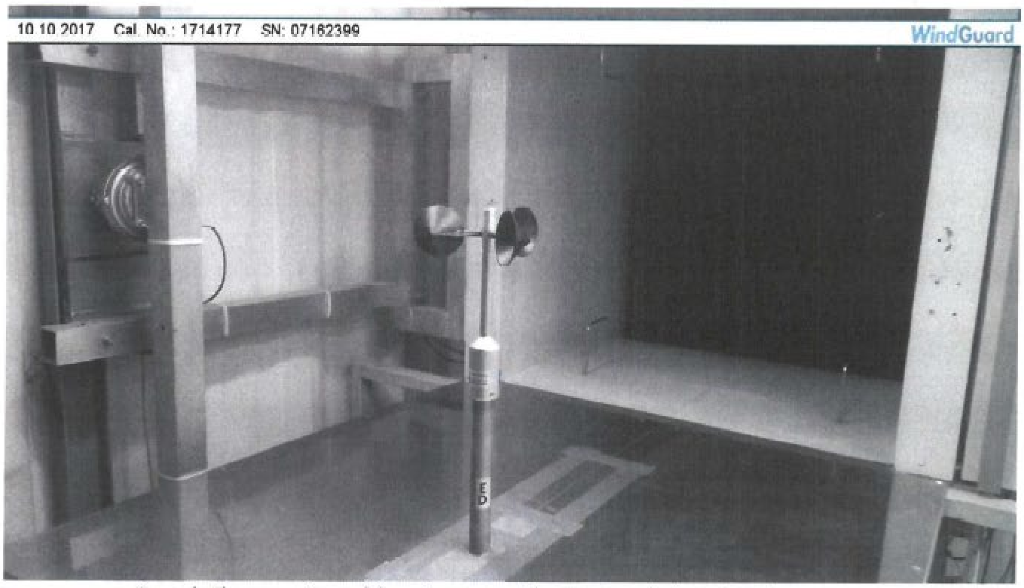


Photo of the measurement setup
Foto des Messaufbaus



Remark: The proportions of the set-up may not be true to scale due to imaging geometry.

APPENDIX F IEC ANNEX L UNCERTAINTY ANALYSES

1. Reference / anemometer uncertainty

The anemometer uncertainty of the specific reference heights is calculated based on the wind tunnel calibration of the individual anemometer, the anemometer classification and the mounting effect at the met tower.

2. Mean deviation of the remote sensor measurements and the reference measurements

This is the relative deviation between the bin averages of the RSD and the mast reference measurement divided by with the reference measurement.

3. Standard uncertainty of the measurement of the remote sensing device

The standard deviation of the measurements was divided by the square root of the number of data records per bin. The relative uncertainty was calculated by dividing the value by the bin average wind speed of the mast (reference) measurement.

4. Mounting uncertainty of the remote sensor at the verification test

The uncertainty of the remote sensing device due to non-ideal levelling was estimated to be 0.5 %.

5. Uncertainty due to non-homogenous flow

The Lidar device is located in close proximity of the met tower just a few m to the East of the tower base. As a result the uncertainty due to non-homogenous flow within the measurement volume is considered to be negligible.

APPENDIX G ENVIRONMENTAL CONDITION DURING THE VERIFICATION CAMPAIGN

Height level 92m																			
BIN lower	BIN upper	nbin	Vmm	Wind direction		Turbulence Intensity		Shear coef. between 92-21m		Wind veer between 88-43.5m		Temperature gradient		Air temperature		Air density		LiDAR Data Quality	
[m/s]	[m/s]	#	Avg [m/s]	Avg [°]	Std [°]	Avg [-]	Std [-]	Avg #	Std #	Avg [°/m]	Std [°/m]	Avg [K/m 10^2]	Std [K/m 10^2]	Avg [°C]	Std [°C]	Avg [kg/m³]	Std [kg/m³]	Avg [% or -]	Std [% or -]
3.75	4.25	136	4.03	236.01	49.77	0.12	0.06	0.30	0.3	-1.9	2.2	-0.5	1.2	17.0	4.9	1.204	0.021	34.76	3.71
4.25	4.75	134	4.53	233.34	47.39	0.12	0.06	0.31	0.2	-2.0	2.2	-0.5	0.9	17.1	4.4	1.203	0.018	34.51	3.98
4.75	5.25	143	5.00	228.70	41.18	0.11	0.05	0.35	0.3	-2.1	2.3	-0.6	1.0	17.0	4.5	1.204	0.020	35.03	2.77
5.25	5.75	223	5.49	232.52	42.56	0.11	0.05	0.31	0.2	-2.3	2.0	-0.5	1.1	16.7	4.0	1.206	0.018	34.77	3.42
5.75	6.25	213	5.99	231.68	38.12	0.11	0.05	0.30	0.2	-2.6	1.6	-0.6	1.0	16.1	3.1	1.209	0.015	34.96	2.51
6.25	6.75	223	6.50	221.53	36.54	0.11	0.05	0.32	0.2	-2.3	2.2	-0.5	1.0	16.0	3.4	1.208	0.016	34.78	3.41
6.75	7.25	248	7.00	219.55	37.97	0.10	0.04	0.30	0.2	-2.4	2.2	-0.6	1.0	15.5	3.0	1.208	0.016	35.03	3.31
7.25	7.75	213	7.47	224.21	31.75	0.11	0.04	0.26	0.2	-2.7	1.8	-0.8	0.6	15.9	2.6	1.206	0.014	35.18	3.03
7.75	8.25	207	8.01	222.12	33.38	0.10	0.04	0.25	0.1	-2.7	1.8	-0.8	0.6	15.6	2.1	1.206	0.013	34.83	3.90
8.25	8.75	230	8.48	218.95	29.58	0.11	0.04	0.24	0.1	-2.9	1.5	-0.8	0.6	15.4	1.8	1.206	0.013	35.23	2.50
8.75	9.25	200	8.99	220.48	37.25	0.12	0.04	0.20	0.1	-2.6	1.9	-1.0	0.5	16.4	1.9	1.201	0.012	34.25	3.84
9.25	9.75	175	9.50	217.67	31.99	0.12	0.03	0.19	0.1	-2.6	2.1	-1.1	0.4	16.6	1.7	1.199	0.011	34.61	3.45
9.75	10.25	123	9.99	221.46	29.98	0.12	0.04	0.20	0.1	-2.5	2.1	-1.1	0.4	16.6	1.7	1.196	0.011	34.41	4.12
10.25	10.75	86	10.45	218.13	36.41	0.12	0.04	0.21	0.1	-2.3	2.4	-1.0	0.5	16.5	1.5	1.195	0.012	32.28	6.81
10.75	11.25	87	10.99	205.75	25.07	0.13	0.03	0.21	0.1	-2.2	2.8	-1.1	0.3	16.6	1.5	1.190	0.012	33.16	5.97
11.25	11.75	51	11.48	208.38	24.73	0.13	0.02	0.21	0.1	-2.5	2.6	-1.1	0.2	16.7	1.4	1.189	0.012	33.12	5.31
11.75	12.25	46	12.00	200.89	16.21	0.13	0.02	0.22	0.1	-2.3	2.9	-1.0	0.2	16.6	1.5	1.187	0.012	33.11	4.73
12.25	12.75	32	12.50	206.29	15.44	0.13	0.02	0.20	0.1	-2.9	2.2	-1.0	0.3	16.8	1.4	1.186	0.011	33.59	4.78
12.75	13.25	28	12.96	209.61	15.20	0.14	0.03	0.20	0.1	-2.7	2.4	-1.1	0.2	17.0	1.3	1.182	0.008	35.18	2.63
13.25	13.75	12	13.47	200.82	16.55	0.14	0.02	0.18	0.1	-1.7	3.4	-1.1	0.2	17.9	1.8	1.175	0.009	35.42	0.90
13.75	14.25	13	13.99	211.24	15.04	0.14	0.02	0.18	0.0	-2.9	2.1	-1.1	0.2	17.7	1.4	1.179	0.008	35.62	1.50
14.25	14.75	13	14.50	211.32	9.93	0.13	0.02	0.19	0.0	-3.5	0.2	-1.1	0.1	17.0	1.2	1.183	0.006	34.77	1.79
14.75	15.25	6	14.99	208.26	12.04	0.12	0.02	0.20	0.1	-3.6	0.3	-1.2	0.2	17.0	1.5	1.182	0.007	36.00	1.26
15.25	15.75	7	15.56	214.30	13.35	0.12	0.02	0.17	0.0	-3.5	0.3	-1.2	0.1	16.9	1.5	1.185	0.002	33.00	4.51
15.75	16.25	9	16.01	213.37	15.02	0.14	0.02	0.17	0.1	-3.5	0.3	-1.2	0.1	16.7	1.7	1.184	0.004	34.89	2.15

Height level 71m																			
BIN lower	BIN upper	nbin	Vmm	Wind direction		Turbulence Intensity		Shear coef. between 92-21m		Wind veer between 88-43.5m		Temperature gradient		Air temperature		Air density		LiDAR Data Quality	
[m/s]	[m/s]	#	Avg [m/s]	Avg [°]	Std [°]	Avg [-]	Std [-]	Avg #	Std #	Avg [°/m]	Std [°/m]	Avg [K/m 10^2]	Std [K/m 10^2]	Avg [°C]	Std [°C]	Avg [kg/m³]	Std [kg/m³]	Avg [% or -]	Std [% or -]
3.75	4.25	156	4.02	229.10	46.19	0.12	0.05	0.3	0.2	-2.1	2.2	-0.5	0.9	16.9	4.7	1.204	0.020	34.58	3.58
4.25	4.75	167	4.50	227.67	45.02	0.12	0.06	0.3	0.2	-2.1	2.3	-0.4	1.1	17.5	4.5	1.201	0.019	34.57	3.65
4.75	5.25	208	5.00	226.53	38.92	0.11	0.05	0.3	0.2	-2.4	2.0	-0.5	1.0	16.3	4.0	1.208	0.018	35.02	2.45
5.25	5.75	234	5.48	229.26	39.79	0.12	0.06	0.3	0.2	-2.4	1.9	-0.5	1.2	16.2	3.5	1.208	0.017	34.82	2.93
5.75	6.25	238	6.00	226.10	40.01	0.12	0.05	0.3	0.2	-2.5	1.9	-0.6	1.1	15.9	3.1	1.208	0.015	34.90	2.92
6.25	6.75	245	6.50	219.20	34.06	0.11	0.04	0.3	0.1	-2.4	2.3	-0.7	0.7	15.7	3.0	1.208	0.015	35.09	2.87
6.75	7.25	194	6.99	227.80	37.82	0.12	0.04	0.2	0.1	-2.3	2.1	-0.9	0.6	15.9	2.9	1.206	0.015	34.39	4.10
7.25	7.75	227	7.48	216.59	33.56	0.12	0.04	0.2	0.1	-2.7	1.9	-0.8	0.6	15.6	2.2	1.206	0.013	34.97	3.76
7.75	8.25	215	7.99	220.51	30.52	0.12	0.04	0.2	0.1	-2.9	1.4	-0.8	0.6	15.7	1.9	1.204	0.012	35.08	3.10
8.25	8.75	180	8.50	220.62	37.84	0.12	0.04	0.2	0.1	-2.4	2.1	-0.9	0.6	16.0	1.8	1.201	0.012	35.09	2.38
8.75	9.25	173	8.97	222.55	32.62	0.14	0.03	0.2	0.1	-2.7	1.9	-1.1	0.5	16.7	1.8	1.198	0.011	34.64	2.96
9.25	9.75	150	9.49	219.80	30.80	0.13	0.03	0.2	0.1	-2.5	2.2	-1.2	0.4	17.0	1.5	1.197	0.011	34.37	4.04
9.75	10.25	98	10.00	213.86	32.42	0.13	0.03	0.2	0.1	-2.1	2.7	-1.1	0.3	16.7	1.4	1.193	0.012	33.21	5.38
10.25	10.75	80	10.48	209.24	26.45	0.14	0.03	0.2	0.1	-2.6	2.4	-1.1	0.3	16.6	1.6	1.191	0.012	32.88	5.59
10.75	11.25	60	10.98	212.02	23.32	0.14	0.02	0.2	0.1	-2.8	2.1	-1.1	0.3	16.8	1.1	1.190	0.012	34.73	2.83
11.25	11.75	41	11.50	203.56	18.62	0.14	0.03	0.2	0.1	-2.5	2.7	-1.0	0.3	16.6	1.7	1.187	0.012	34.10	3.74
11.75	12.25	36	11.99	203.74	13.65	0.14	0.02	0.2	0.1	-2.3	2.9	-1.1	0.2	17.1	1.4	1.183	0.010	34.47	3.33
12.25	12.75	15	12.48	211.43	15.35	0.15	0.04	0.2	0.1	-3.0	1.9	-1.1	0.2	17.0	1.5	1.183	0.008	34.53	3.27
12.75	13.25	15	12.98	206.59	21.53	0.15	0.02	0.2	0.1	-1.5	3.3	-1.2	0.2	18.2	1.5	1.177	0.011	35.47	0.83
13.25	13.75	16	13.49	210.77	11.78	0.14	0.02	0.2	0.0	-3.5	0.3	-1.1	0.1	17.3	1.4	1.181	0.008	35.75	1.18
13.75	14.25	10	13.93	216.11	8.16	0.14	0.02	0.2	0.0	-3.4	0.2	-1.1	0.2	17.2	1.0	1.183	0.004	35.50	1.27
14.25	14.75	5	14.56	208.19	14.34	0.13	0.01	0.2	0.0	-3.6	0.3	-1.2	0.1	17.2	1.8	1.182	0.007	35.40	1.14
14.75	15.25	9	15.04	211.99	12.94	0.15	0.02	0.2	0.0	-3.5	0.3	-1.1	0.1	16.5	1.5	1.184	0.004	33.56	3.50
15.25	15.75	8	15.55	212.30	16.58	0.14	0.02	0.2	0.0	-3.5	0.4	-1.2	0.1	16.6	1.7	1.185	0.003	35.88	1.13
15.75	16.25	4	16.08	222.71	12.80	0.15	0.03	0.2	0.0	-3.3	0.3	-1.2	0.1	18.0	1.5	1.181	0.003	35.75	1.26

Height level 46m																			
BIN lower	BIN upper	nbin	Vmm	Wind direction		Turbulence Intensity		Shear coef. between 92-21m		Wind veer between 88-43.5m		Temperature gradient		Air temperature		Air density		LiDAR Data Quality	
[m/s]	[m/s]	#	Avg [m/s]	Avg [°]	Std [°]	Avg [-]	Std [-]	Avg #	Std #	Avg [°/m]	Std [°/m]	Avg [K/m 10^2]	Std [K/m 10^2]	Avg [°C]	Std [°C]	Avg [kg/m³]	Std [kg/m³]	Avg [% or -]	Std [% or -]
3.75	4.25	231	3.99	216.65	38.73	0.12	0.06	0.3	0.2	-2.6	1.8	-0.3	1.1	16.7	4.2	1.206	0.019	33.52	4.81
4.25	4.75	203	4.50	213.60	46.01	0.12	0.05	0.3	0.1	-2.1	2.3	-0.3	1.4	17.0	4.3	1.204	0.019	34.09	4.34
4.75	5.25	256	5.01	219.09	43.35	0.14	0.06	0.2	0.1	-2.3	2.1	-0.5	1.2	16.2	3.6	1.206	0.016	33.70	4.90
5.25	5.75	243	5.48	217.02	36.06	0.13	0.04	0.2	0.1	-2.6	1.8	-0.7	0.7	15.4	2.4	1.210	0.013	33.86	4.72
5.75	6.25	235	5.99	215.73	37.61	0.13	0.04	0.2	0.1	-2.2	2.3	-0.8	0.6	15.8	3.1	1.207	0.016	33.73	4.79
6.25	6.75	233	6.50	215.98	39.27	0.13	0.04	0.2	0.1	-2.2	2.2	-0.8	0.6	15.7	2.6	1.206	0.014	34.19	4.36
6.75	7.25	216	7.01	216.20	32.93	0.14	0.04	0.2	0.1	-2.8	1.6	-0.9	0.6	15.9	2.5	1.204	0.014	34.24	4.70
7.25	7.75	187	7.49	210.62	34.51	0.14	0.04	0.2	0.1	-2.5	2.1	-0.9	0.6	15.8	2.0	1.202	0.012	34.87	3.21
7.75	8.25	148	7.98	218.30	30.57	0.15	0.04	0.2	0.1	-2.6	2.0	-1.1	0.4	16.4	1.7	1.200	0.011	34.16	3.97
8.25	8.75	176	8.50	221.55	35.80	0.15	0.03	0.2	0.1	-2.4	2.2	-1.2	0.3	17.0	1.6	1.196	0.011	33.18	5.04
8.75	9.25	145	9.00	215.19	28.07	0.15	0.03	0.1	0.0	-2.7	2.0	-1.2	0.2	17.1	1.4	1.196	0.012	33.83	4.43
9.25	9.75	102	9.47	210.40	27.24	0.15	0.03	0.2	0.0	-2.6	2.3	-1.1	0.3	16.7	1.5	1.193	0.012	32.75	5.61
9.75	10.25	78	10.00	208.12	22.64	0.16	0.03	0.2	0.0	-2.9	2.0	-1.2	0.2	16.8	1.3	1.191	0.012	34.04	3.95
10.25	10.75	50	10.50	206.53	19.75	0.15	0.03	0.2	0.0	-2.6	2.5	-1.1	0.3	16.8	1.4	1.189	0.013	35.08	2.05
10.75	11.25	34	10.99	205.84	18.29	0.16	0.02	0.2	0.0	-2.4	2.7	-1.1	0.2	17.4	1.4	1.183	0.011	34.41	2.63
11.25	11.75	17	11.43	202.91	16.68	0.17	0.02	0.2	0.0	-2.2	2.9	-1.1	0.2	17.0	1.6	1.183	0.009	34.35	3.77
11.75	12.25	17	12.01	207.48	18.53	0.17	0.04	0.2	0.0	-2.1	2.9	-1.2	0.2	17.9	1.4	1.179	0.011	35.00	1.66
12.25	12.75	20	12.52	211.19	12.48	0.16	0.02	0.2	0.0	-3.5	0.3	-1.1	0.2	17.2	1.4	1.182	0.008	35.65	1.14
12.75	13.25	8	12.96	218.31	6.54	0.15	0.02	0.1	0.0	-3.3	0.1	-1.2	0.1	17.9	0.7	1.182	0.004	35.88	1.25
13.25	13.75	7	13.50	212.05	14.50	0.15	0.02	0.1	0.0	-3.5	0.3	-1.2	0.1	17.3	1.5	1.182	0.006	35.00	1.15
13.75	14.25	7	14.08	210.69	13.16	0.16	0.01	0.1	0.0	-3.5	0.3	-1.2	0.1	16.6	1.7	1.184	0.004	33.57	2.99
14.25	14.75	8	14.47	210.88	15.71	0.16	0.02	0.1	0.0	-3.5	0.4	-1.2	0.1	16.6	1.6	1.184	0.003	35.88	1.13
14.75	15.25	6	15.01	212.30	14.84	0.14	0.02	0.2	0.0	-3.4	0.3	-1.2	0.2	17.0	1.7	1.183	0.003	36.33	0.52
15.25	15.75	4	15.33	227.65	4.80	0.15	0.01	0.1	0.0	-3.1	0.1	-1.2	0.1	18.6	0.2	1.181	0.003	35.75	0.50
15.75	16.25	4	16.03	212.22	15.19	0.14	0.02	0.1	0.0	-3.4	0.3	-1.2	0.1	16.8	2.1	1.183	0.005	34.25	2.06

Height level 21m																			
BIN lower	BIN upper	nbin	Vmm	Wind direction		Turbulence Intensity		Shear coef. between 92-21m		Wind veer between 88-43.5m		Temperature gradient		Air temperature		Air density		LiDAR Data Quality	
[m/s]	[m/s]	#	Avg [m/s]	Avg [°]	Std [°]	Avg [-]	Std [-]	Avg #	Std #	Avg [°/m]	Std [°/m]	Avg [K/m 10^2]	Std [K/m 10^2]	Avg [°C]	Std [°C]	Avg [kg/m³]	Std [kg/m³]	Avg [% or -]	Std [% or -]
3.75	4.25	240	4.00	210.76	37.98	0.15	0.04	0.3	0.1	-2.4	2.2	-0.5	1.0	16.4	3.9	1.205	0.018	29.85	3.88
4.25	4.75	260	4.50	216.30	39.45	0.16	0.05	0.2	0.1	-2.3	2.2	-0.8	0.5	15.8	3.1	1.208	0.015	30.50	3.83
4.75	5.25	251	5.00	221.47	35.39	0.16	0.04	0.2	0.1	-2.4	1.9	-0.8	0.6	15.4	2.6	1.209	0.014	30.94	3.81
5.25	5.75	236	5.51	215.46	40.64	0.16	0.04	0.2	0.1	-2.1	2.4	-0.9	0.5	16.1	3.4	1.204	0.015	30.74	4.04
5.75	6.25	224	6.00	214.81	37.40	0.16	0.03	0.2	0.1	-2.5	2.0	-0.9	0.5	16.0	2.7	1.204	0.014	31.23	3.38
6.25	6.75	171	6.48	215.52	36.68	0.17	0.03	0.2	0.1	-2.4	2.1	-1.1	0.4	16.3	2.1	1.200	0.012	30.64	3.49
6.75	7.25	160	7.01	217.55	33.00	0.17	0.03	0.1	0.1	-2.4	2.3	-1.2	0.3	16.6	1.5	1.197	0.010	30.74	3.16
7.25	7.75	164	7.50	222.22	34.28	0.17	0.03	0.1	0.0	-2.4	2.1	-1.2	0.2	17.0	1.5	1.197	0.011	30.71	3.48
7.75	8.25	168	8.00	215.82	27.92	0.17	0.03	0.1	0.0	-2.9	1.7	-1.2	0.2	17.0	1.5	1.195	0.011	30.74	3.66
8.25	8.75	128	8.47	214.63	27.35	0.17	0.03	0.1	0.0	-2.7	2.0	-1.2	0.2	17.0	1.5	1.194	0.013	31.78	3.28
8.75	9.25	72	8.98	207.24	21.27	0.17	0.03	0.1	0.0	-2.8	2.1	-1.2	0.3	16.8	1.3	1.192	0.013	30.36	5.49
9.25	9.75	55	9.49	210.83	19.46	0.17	0.03	0.1	0.0	-2.7	2.2	-1.2	0.2	17.2	1.3	1.189	0.012	31.42	4.44
9.75	10.25	24	9.97	209.82	19.60	0.18	0.03	0.1	0.0	-2.5	2.5	-1.2	0.2	17.4	1.4	1.184	0.010	31.42	5.63
10.25	10.75	17	10.50	204.06	19.14	0.19	0.03	0.2	0.0	-1.7	3.2	-1.2	0.2	17.8	1.5	1.179	0.011	32.65	1.77
10.75	11.25	18	10.99	211.87	13.58	0.17	0.02	0.2	0.0	-3.5	0.3	-1.1	0.2	17.7	1.4	1.181	0.009	33.72	1.67
11.25	11.75	12	11.48	214.35	11.74	0.17	0.02	0.1	0.0	-3.4	0.3	-1.2	0.1	17.4	1.1	1.183	0.007	33.42	2.39
11.75	12.25	7	11.96	219.43	8.38	0.17	0.02	0.1	0.0	-3.3	0.2	-1.2	0.1	17.7	1.1	1.182	0.002	33.86	1.68
12.25	12.75	9	12.60	205.66	12.23	0.17	0.02	0.1	0.0	-3.6	0.3	-1.1	0.1	16.0	1.4	1.186	0.002	32.56	1.42
12.75	13.25	11	13.00	211.98	14.54	0.17	0.02	0.2	0.0	-3.5	0.3	-1.2	0.1	16.9	1.7	1.184	0.004	34.73	1.27
13.25	13.75	5	13.62	227.94	4.21	0.17	0.01	0.1	0.0	-3.1	0.1	-1.2	0.1	18.6	0.2	1.180	0.002	34.80	1.30
13.75	14.25	3	13.98	216.79	14.57	0.17	0.02	0.1	0.0	-3.3	0.3	-1.2	0.2	17.3	2.0	1.182	0.005	33.00	1.73
14.25	14.75	4	14.47	219.58	14.49	0.17	0.03	0.1	0.0	-3.3	0.3	-1.3	0.1	17.7	1.8	1.182	0.004	33.25	0.96
14.75	15.25	2																	
15.25	15.75	0																	
15.75	16.25	1																	

About DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our 12,000 professionals are dedicated to helping our customers make the world safer, smarter and greener.